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# APPLICATION OF THE QSDC PROCEDURE TO THE FORMULATION OF SPACE SHUTTLE DESIGN CRITERIA

## VOLUME II. APPLICATIONS GUIDE

by:

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Gary L. Martin

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# APPLICATION OF THE QSDC PROCEDURE TO THE FORMULATION OF SPACE SHUTTLE DESIGN CRITERIA

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Technology Incorporated

## FOREWORD

This report was prepared by Technology Incorporated under Contract NAS8-26918, the "Establishment of Statistically Based Criteria for Determining the Probability of Structural Failure," for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Astronautics Laboratory of the George C. Marshall Space Flight Center.

All work was conducted at the Information Systems Division of Technology Incorporated, 3821 Colonel Glenn Highway, Dayton, Ohio, 45431, from 13 April 1971 to 13 March 1972. Mr. Innes Bouton was the Program Manager and Principal Investigator under the administrative guidance of Mr. Dudley C. Ward. The results of this study have been documented in this final report, identified as Technology Incorporated Report No. 425-72-14.

This report has been reviewed and is approved.

Dudley C. Ward
DUDLEY C. WARD
Manager,
Aeromechanics Department

ABSTRACT

As documented by a two-volume report, criteria to determine the probability of aircraft structural failure were established according to the Quantitative Structural Design Criteria by Statistical Methods, the QSDC Procedure. This criteria method was applied to the design of the space shuttle during this contract. An Applications Guide was developed to demonstrate the utilization of the QSDC Procedure, with examples of the application to a hypothetical space shuttle illustrating the application to specific design problems. Discussions of the basic parameters of the QSDC Procedure: the Limit and Omega Conditions, and the strength scatter, have been included. Available data pertinent to the estimation of the strength scatter have also been included.

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## 1. INTRODUCTION

Engineers have long recognized a need for reliability-based structural design criteria. Present design methods have not produced structures that are consistently reliable simply because there is no means to consider reliability as a design factor. On the other hand, most of the proposed reliability methods are not practical in their application as design methods. The reliability methods previously proposed have the common fault of assuming that the strength distribution of the structure (the normal variation of nominally identical structures of a design) and the loads to which the structure is subjected are known. That is, they do not consider the possibility of an error in the analysis such that the actual strength distribution is different than the predicted strength distribution. The neglect of the error-disclosing ability of a test and the necessity of a proof of compliance procedure have also been common. The design procedure which can encompass both reliability and the practical aspects of the Present System will be the optimum design procedure. A design procedure which blends the aspects of reliability and practicality into a consistent, useful design procedure has been proposed in the "Quantitative Structural Design Criteria by Statistical Methods," the QSDC Procedure (Reference 1).

As a design procedure that can blend reliability with the practical aspects of structural design criteria, the QSDC Procedure must define design criteria in terms of reliability and then translate them into design requirements that can be met in a practical design procedure. The QSDC accomplishes this by specifying design requirements that interface with the present design procedures. That is, deterministic strength requirements are specified and must be demonstrated by the appropriate proof of compliance procedure. However, the original development of the QSDC Procedure as presented in AFFDL-TR-67-107 discussed the basic concepts without developing explicit methodology and the necessary data base required for its application. In fulfillment of this need, the Applications Guide was developed.

The Applications Guide was developed as a handbook that structural design engineers could use in implementing the QSDC Procedure as a structural design criteria method. The QSDC Procedure is presented as a stepwise procedure in which the design conditions, design factors, and design loads (strength requirements) are specified. Proof of Design is provided by appropriate analyses and tests such as those described in NASA SP-8057 (Reference 2). Static and fatigue strength requirements are discussed in Section 2. Thermal design problems, although not discussed here, are outlined in Volume 1. The important parameters in the QSDC Procedure are the strength scatter coefficient and the design and test factor of safety. These parameters and their relation are discussed in Section 3. Also, data on the strength scatter coefficient is presented in Section 3. Examples illustrating the choice of design conditions and design factors can be found in Section 4. These examples are representative of the Phase B configuration of the Space Shuttle. Although care was taken so that the examples would be independent of any particular structure, specific design problems were considered to demonstrate that the QSDC Procedure is specific in its application although it is general in its nature.

## 2. QSDC METHODOLOGY

### 2.1 Intent of the QSDC Procedure

#### 2.1.1 General

In the implementation of a new design procedure such as the QSDC Procedure, it is often helpful to describe the intent of the procedure. If the new procedure does not cover a specific design problem, the engineer can, with an understanding of the intent of the procedure, arrive at a solution to that particular problem.

First, the basic intent of any structural design procedure should be to ensure that the structure is of sufficient strength and reliability to perform its intended function in its particular environment for the planned lifetime of the vehicle. This goal is achieved through the QSDC Procedure by establishing a design methodology which will result in structural systems that will rarely fail during operations. The QSDC solution is designed to take explicit and active measures to prevent structural failures for all service conditions ranging in severity from zero to infinity. To prevent failures in all possible environmental situations, the design spectrum is subdivided into three separate operational regions as shown in Appendix A (Figure 2, page A-6). Failure is then prevented in each region. These three regions - safe, overload, and gross overload - are delimited by two deterministically defined operational conditions: the Limit Condition and the Omega Condition.

These two conditions are intended to represent interfaces between the structural and non-structural systems. The determination of the Limit and Omega Conditions is described in detail in Section 2.2.2. The intent behind the choice of the two conditions is summarized below.

The Limit Condition is intended to be the upper boundary of normal and expected operations of the vehicle and its non-structural subsystems. This qualitative definition is quantitized in the QSDC Procedure as discussed in Section 2.2.2. For instance, the Limit Condition might be defined as a $2\sigma$ or a one-in-one-hundred condition. For all practical purposes, the Limit Condition in the QSDC Procedure is intended to be the same as the Limit Condition in the Present System (represented by Reference 2). Since a Limit Condition is normal and expected, it should be permissible to operate at all operational levels up to and including the Limit Condition. Typically, operational limitations and placards are related to Limit Conditions.

Since the Limit Condition is a permissible condition, it should be structurally "safe" to operate up to the Limit Condition. Thus, the Limit Condition has the characteristic of an interface between the structural and non-structural systems.

The non-structural system may be operated up to Limit with every expectation that structural survival is "certain" and will result in operations that are "safe." If a structural failure should occur at an operational condition below Limit, responsibility for the failure must be attributed to the structural system.

The Omega Condition is intended to represent the most extreme or severe operational condition for which some degree of structural capability is required. Operations beyond Limit must be considered as overload situations imposed on the structural system by the non-structural system. The Omega Condition is intended to establish a bound on the overload from non-structural systems that the structural system must tolerate and survive. Any operation beyond the bound established by the Omega Condition is considered to be a gross overload and is not expected to be survivable.

Although the Omega terminology is new, the concept of providing structural capability beyond the Limit Condition is not. The 1.5 Factor of Safety that is typical in the Present System provides some overload capability although the amount varies from one design to the next. The QSDC Procedure differs from the Present System only by making the overload requirement explicit. The QSDC Procedure rationalizes the overload requirement by linking it to a structural reliability requirement. This rationalization of the overload requirement can be understood and accepted if it is realized that the average structure in a fleet must survive (to a first approximation) a flight condition that occurs once in the lifetimes of a 1000 vehicles if a 0.999* reliability is to be attained. Conversely, it is not necessary to provide more strength than enough to survive an operational condition which is the complement of the desired structural reliability.

Thus, the intent in establishing the Omega Condition in the QSDC Procedure is to define an upper bound on operational mode for which some capability of surviving structurally is required. Since the structure is not required to survive beyond the Omega Condition, the vehicle must not exceed this condition too often or the structure may fail so often that the structural reliability goal cannot be met.

The requirements for the structural system are related to the Limit and Omega Conditions in the QSDC Procedure. As noted in the discussion of the Limit Condition, the QSDC Procedure intent is to define requirements that will result in a structural system which is "safe" if the Limit Condition is not exceeded. Reference 1 quantitatively defines a structure which is "safe" in the region up to the Limit Condition as one which has no more than one percent of its total failure distribution below the

* Typical numbers. Specific values depend on vehicle mission as discussed in Section 2.2.2.

Limit Condition. This means that, for any specified reliability goal, the contribution to the failure rate will be insignificant in the "safe" region. There should be no more than one failure in the "safe" region below the Limit Condition for every 99 failures in the overload regions above Limit.

The desired high degree of certainty of survival in the "safe" region is obtained in the QSDC Procedure by designing and testing to the Limit Loads multiplied by a factor of safety known as the Limit Design and Test Factor of Safety (LTFS). This is essentially the same procedure as that in the Present System. The difference is that the LTFS in the QSDC Procedure is not a fixed value such as 1.5 but a variable dependent on (1) the reliability goal as defined by mission, (2) the strength scatter, and (3) the number of strength tests of the particular structural configuration (see Figure 6). It is the intent of the QSDC Procedure that the factor of safety (LTFS on Figure 6) be the minimum value required to attain a "safe" structure. Since the overload capability is provided separately, the requirement for "safe" structure up to the Limit Condition can be established without consideration of overload capability and total probability of failure.

References 3 and 4 together with Section 2.1.2 and Appendix B of this report discuss the possibility of errors in the strength analysis. A basic premise in the QSDC Procedure is that the frequency and magnitude of analytical errors are major contributors to structural unreliability. The desired level of structural reliability is regained by strength tests which disclose any errors with a high degree of certainty. The error disclosure results in rejection of the unreliable design followed by redesign and retest until the test requirements are satisfied.

The LTFS of Figure 6 is intended to define design and test loads incremented upward from Limit Loads sufficiently so that a service vehicle will "never" fail at the unfactored Limit Load after being tested to the higher design loads factored upward by the LTFS. Reference 1 describes how the LTFS is calculated. Oversimplified, it is determined by the range between the high side and the low side of the strength distribution of the particular structural system. There is a finite possibility that an understrength design might pass the static test because the test article is randomly on the high side of the actual mean strength. This situation is sometimes called "random success." Such an understrength design would be approved for production, not knowing that the design is understrength and that the mean strength is below the test strength. Some of the flight articles would inevitably be below the mean strength which is already below the test strength. To attain a "safe" design, one with a very low probability of failure at Limit, the chance must be minimized of a random success on the high side of the true strength distribution resulting in the qualification of an understrength structural design which is followed by a random low side failure of one of the operational vehicles. The larger the strength scatter, the larger the range between the high side and the low side at a given probability level. This is the underlying reason why the LTFS must increase as the strength scatter increases as shown on Figure 6.

Designing and testing as necessary to attain a structural configuration which is "safe" up to the Limit Condition will not necessarily result in the desired total probability of failure and overall structural reliability. The total probability of failure is related to the frequency and magnitude with which the Limit Condition is exceeded operationally. Reference 1 establishes that in most situations structures which are designed and tested to the loads corresponding to the Omega Condition will intrinsically have a probability of failure less than the probability of exceedance of the Omega Condition. However, when the strength scatter is large, the structural reliability starts dropping if the test load is the same as the load associated with the Omega Condition. As shown on Figure 7 a separate factor of safety (OTFS) must be applied to the Omega Loads when the strength scatter is large.

If the intent of the QSDC Procedure is accomplished, the resulting structural system will satisfactorily perform its function as a vehicle subsystem. The structure will be "safe" and "never" fail in the operational region up to the Limit Condition. Since this region is by designation the region of normal and expected operations, almost all operational situations occurring in actual usage will be in this "safe" region.

The intent of the QSDC Procedure is that a negligible proportion of the total probability of failure distribution will occur in the region below the Limit Condition. Therefore, the major contribution to the total probability of failure will result from operations in the overload and gross overload regions (see Figures 2 and 4 of Appendix A). Regardless of the calculated probability of failure based on the predicted probability of exceedance of the Limit Condition, any failure beyond the Limit Condition is the result of an operational overload. The first and best line of defense against such failures is to conduct service operations of the vehicle and its non-structural subsystems so that the designated Limit Condition will not be exceeded. If the effort to prevent overload operations is successful, the Limit Condition requirement, designing for Limit Loads multiplied by the LTFS, will provide for "safe" operations.

If the Limit Condition is penetrated and overload operations do occur, the second line of defense is the overload capability of the structural system provided by the Omega Condition requirement. The intent of the QSDC Procedure is to define Omega requirements which result in a structural system with "most" of the operational vehicles capable of surviving a penetration of the overload region between the Limit and the Omega Conditions. "Most" is used to define the requirement since penetration into the overload region will be rare, and if "most" vehicles survive the penetration, failure will be very rare in this region.

If the penetration of a Limit Condition continues beyond the Omega Condition, survival of the structure is not likely. It is the intent of the QSDC Procedure that prevention of structural failure due to a gross overload caused by operation beyond the Omega Condition should not be the responsibility of the structural system. Prevention of structural failure in the gross overload region beyond Omega is the responsibility of the non-structural system interfacing with the structural system. If operations can be conducted so that the Omega Condition is never exceeded or, at worst, so that the frequency or probability of exceedance is no more than originally predicted when the Omega Condition was established, then the probability of failure and structural reliability will be as originally predicted.

### 2.1.2 Implementation of Intent

The intent described in the previous section must be carried out by specific actions if the "no failure" goal is to be attained while minimizing the structural weight and cost necessary to achieve the goal.

The first step in implementing the intent of the QSDC Procedure is to establish a deterministic interface between the structural and nonstructural systems. This interface is defined by the dual level of operational conditions. The determination of the dual (Limit and Omega) conditions is discussed in Section 2.2.2. Prediction of the lifetime operational spectra on which the determination of the Limit/Omega Condition should be based cannot be expected to be perfectly accurate. Therefore, the QSDC procedure is intended to translate the definition of the Limit/Omega Conditions into operational limitations and performance requirements for nonstructural systems. Those responsible for the design and operation of any nonstructural system interfacing with the structural system must be appraised of the magnitude of the Limit Condition. They, in turn, must be responsible for not exceeding the Limit Condition. When exceedances do occur, it is the intent of the QSDC Procedure that there be an advance commitment that each instance of exceedance of a Limit Condition be investigated and corrective action taken to prevent future exceedance.* It should never be forgotten that structural failure can be caused, as shown on Figure 1 of Appendix A, by excessively severe operations resulting in overloads. Control of operations is equally important with control of strength in preventing structural failures.

* Naturally, a system would be required to monitor the vehicle operation so that exceedances of Limit could be detected.

The intent of "no failure at Limit" is achieved by designing and testing (in most cases) to loads which are higher than those at the Limit Condition. The increment beyond Limit provides a reserve against understrength so that any design which is tested to the specified loads will "never" fail in operations at Limit. The required increment is defined in the QSDC Procedure as a Limit Design and Test Factor of Safety (LTFS). It is explicitly tailored to be the minimum value commensurate with the structural reliability goal for the particular mission. As shown on Figure 6, an LTFS less than 1.5 may be justified in many cases but larger values may be necessary in other cases.

In the past, the conventional 1.5 F.S. has provided this necessary reserve against understrength generally with good success. However, it has done so indirectly, not as the result of a specific requirement. In some instances the 1.5 factor has been more than necessary and in other cases it has not been enough to provide the desired reliability. In such instances, past procedures have proscribed such situations. For example, long slender columns are not permitted in aerospace structures according to MIL-HDBK-5A; pressure vessels usually require a factor of safety greater than 1.5; and brittle materials such as ceramics and extremely high heat treatments are not used in primary structures.

If the reserve against understrengths were to be ignored, as some investigators have proposed, the result is very likely to be an unsafe structure. For example, with no errors in the analysis and fabrication, the specification of a factor of safety of 1.0 would, by present methods, result in a failure rate of one per hundred vehicles at or below Limit. Since the present method matches the "A" allowable (99 percent exceed) of the material strength with the required strength (the load at Limit), the one-in-one-hundred strength that did not exceed the "A" allowable would certainly fail below Limit. Some investigators have not considered the effect of the factor of safety in light of the reserve against this understrength. They have claimed that the factor of safety is necessary to compensate for errors. However, in the previous discussion where no errors are considered, the result is still an unsafe structure when a 1.0 factor of safety is used. Therefore, the factor of safety is used to account for another phenomenon: that of the normal variation or scatter in the strength of the material.

Unfortunately, the problem of designing a structure to be "safe" at Limit is more serious than indicated in the preceding paragraph. Reference 1 points out the difficulty of achieving a "safe at Limit" design when the possibility of an analytical error in the strength analysis is considered. If the Jablecki/Chenoweth data (References 3 and 29) are accepted as valid, approximately one in ten of the analytically qualified designs would fail at Limit (assuming a 1.5 F.S.).

The possibility of these failures can be demonstrated by Figure 1 where the strengths of an inventory of 20 new designs are shown. The strength distribution of each design is shown as a percentage of the Limit Load. These values for the strength distributions are based on the Jablecki/Chenoweth data and represent the initial, untested strength distributions of the design. In keeping with the one-in-ten design failures below Limit, 2 of the 20 design strength distributions, E and K, have their mean strength at or below the Limit Strength. Similarly, the 12 strength distributions whose mean strengths are below 150 percent of the Limit Load level (designs B, D, E, G, I, K, L, N, P, Q, S, and T) represent the 50 percent of the structural designs that will fail below the Design Load. To substantiate the percentages used, reference is made to Figure B-2 where the Jablecki/Chenoweth data are presented. Specific percentages of the design load have been assigned to specific designs for illustrative purposes only. It is pointed out that the underlying assumption of the QSDC Procedure is that the actual location of a design strength distribution is never known with certainty. For example, when a particular system such as the space shuttle is considered, the strength distribution of the design may be that of design A; but it could be like the strength distribution of design N, or worse yet, like the strength distribution of design K. Given a single strength test, it cannot be said with certainty that the strength distribution of the space shuttle is that of design A; instead, in the QSDC Procedure the statement is allowed that the strength distribution of the space shuttle is probably that of design A. The probability that the strength distribution is below the intended location must be considered if a "safe" structure is to be designed.

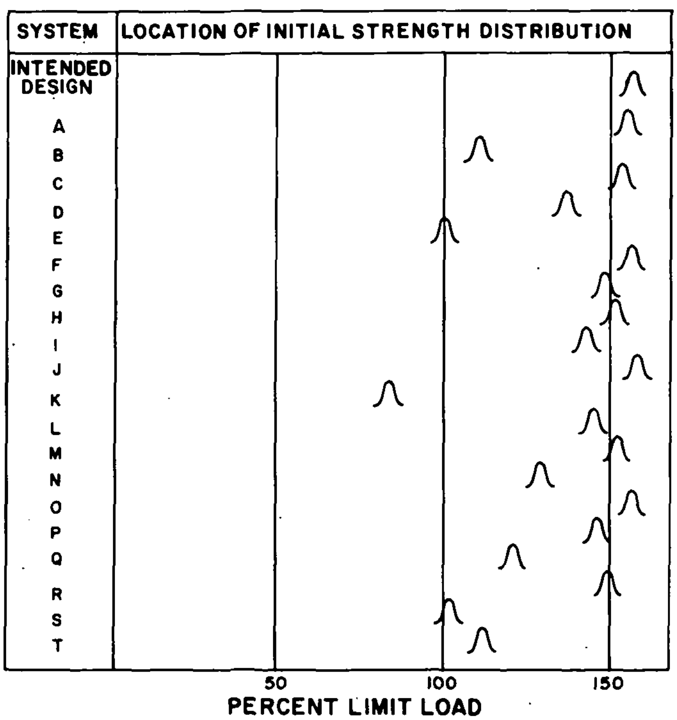


Figure 1. Typical Locations of the Initial Strength Distributions for Jablecki Data

The assumption that space shuttle designs will be as error-prone as the aircraft designs resulting in the Jablecki/Chenoweth data is argumentative. However, available evidence indicates that the assumption is valid. In any event, it is a basic assumption of the QSDC procedure that the strength analysis alone will not result in the high degree of certainty necessary to be sure that a new design will be "safe" at the Limit Condition. References 1 and 5 state the need for designing and testing a design to loads greater than the loads associated with the Limit Condition. The magnitude of the factor depends on the level of structural reliability desired, the coefficient of strength scatter, $\gamma_S$ (see Section 2), and the number of strength tests to be conducted to qualify the design. Figure 6 shows the recommended value of this factor of safety. It is called the Limit Design and Test Factor of Safety (LTFS) to distinguish it from the well-known 1.5 factor of safety.

References 1 and 5 discuss in detail the rationale for the LTFS values shown on Figure 6. Oversimplified, the LTFS is associated with the certainty that the strength qualification test will reveal a deficient design by a failure below the required test load. The certainty of rejection is related to the "random success" phenomena. This means simply that the test article may be stronger than the average strength of nominally identical articles. Therefore, an understrength design may pass the qualification test. The possibility that operational vehicles may fail at Limit after successfully passing a test to some higher load depends on the range in strength from the high side to the low side of the distribution of nominally identical structures. Thus, the larger this range in strength, as defined by $\gamma_S$, the larger the factor of safety necessary to assure "no failure" at Limit. Consequently, the factor of safety is a function of the scatter in strength as shown in Figure 6.

The degree of certainty required so that the new design will be safe at the Limit Condition can be insured by performing a strength test to the design load. The disclosure of the understrength designs (B, D, E, I, K, L, N, P, S, and T) is shown in Figure 2. The short vertical line placed on the strength distribution represents the failing strength of the strength test article. When the strength of the test article is surpassed in the test, the article fails and the design is considered unacceptable (marked by an X on Figure 2). The structure must be redesigned and retested until the test article passes the test to the design load; i.e., the test article strength is greater than the design load. When this situation occurs, the design is qualified (the design strength distribution is crosshatched in the figure to represent the qualified design).

The anomalies that can occur in the strength test are illustrated by designs C, G, and Q. For design C, the strength distribution of the design is satisfactory before the test is conducted, but the strength of the test article is randomly on the low side of the strength distribution. As a result, the test article fails at less than the Design Load and hence the design fails to qualify. (This phenomenon is known as random failure.) The design must be strengthened as a result of the test failure thus strengthening an already satisfactory design. The disadvantage of the random failure is only in the added program cost for the redesign, retest, and additional weight. Design G represents the opposite phenomenon: that of random success. The strength distribution of the design is less than that intended, but the test article is randomly on the high side of the strength distribution. Thus, a design that is slightly understrength passes the strength test and is qualified. However, the Reference 1 data shows that minor understrengths such as in design G do not result in a significant loss in structural reliability.

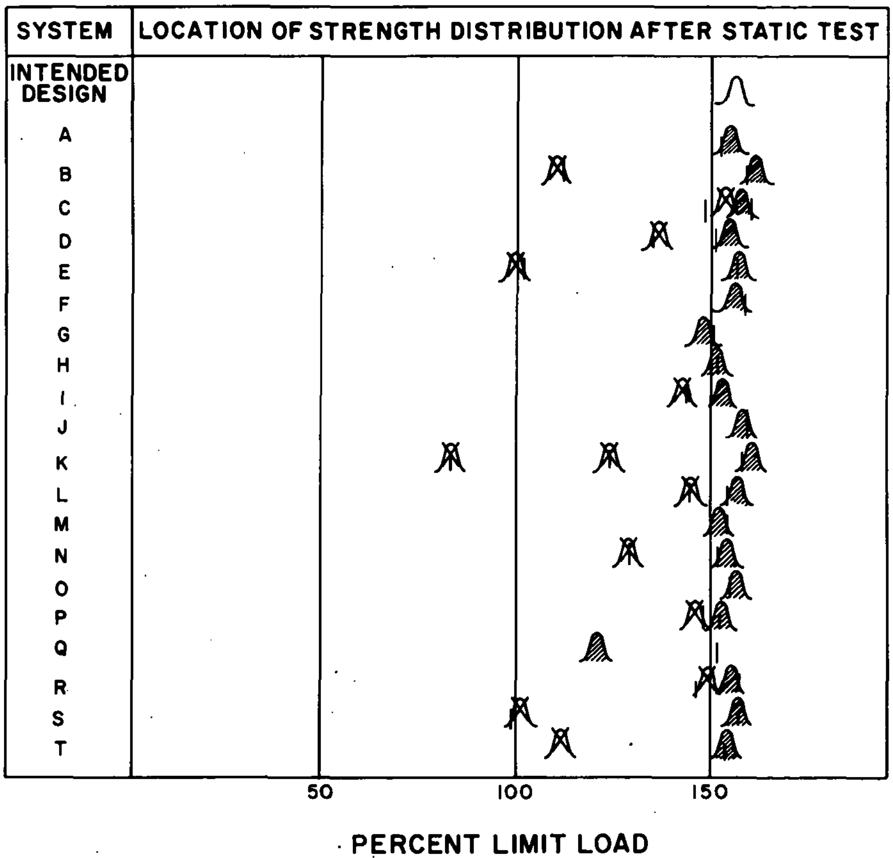


Figure 2. Typical Locations of the Strength Distributions After the Static Test to the Design Load

Design Q is a repetition of the random success phenomenon. The only difference is that the degree of the design understrength is much greater. The design Q is included so that the effect testing has on the certainty of having a "safe" design at the Limit Condition can be demonstrated by a simple example. It is assumed that the factor of safety is 1.5 and that the structural configuration results in a typical strength scatter (coefficient of strength variation equal to 0.05). If it is assumed that an error in the analysis results in a structure whose mean strength is midway between the Limit and Ultimate Loads (Reference 1 points out that this midpoint location of the mean strength is the worst possible case). A successful test to 150 percent of Limit Load would occur only once in 31,500 such situations.* This 1-in-31,500 design, which happened to pass the test to Ultimate Load, would qualify the design and make it acceptable for production. Based on the location of its mean strength, the probability of a service vehicle failing at Limit would also be 1-in-31,500. As a result, the probability of failing at Limit after a successful test to 150 percent Limit is the product of the two probabilities or approximately one in one billion. In the QSDC Procedure this very low probability is considered equivalent to "no" failure. It appears that the rationale outlined above explains why strength tests to 150 percent of Limit Load have resulted in very reliable structural systems in the past.

The intent of the QSDC Procedure as described has been limited to structural reliability as defined by the prevention of catastrophic rupture or collapse of the structural system. Yield in the structure in the region up to Limit has traditionally been considered to be unacceptable. However, yielding in the structural system does not normally cause loss of the vehicle or loss of life. Generally, yield failures result in economic consequences only. The cost reflects the loss of vehicle utility during a mission or the cost of repairing or replacing a yielded component. Therefore, the certainty of surviving up to the Limit Condition without yield may be much less than the certainty of surviving Limit without catastrophic failure.

If a structural reliability goal based on survival without yield can be defined, the yield factor of safety can be developed in the same manner as the LTFS for ultimate or catastrophic failure as defined on Figure 6. The determination of specific values for the yield factor of safety is beyond the scope of the present study. However, it appears reasonable to assume that the reliability against the yield mode of failure could be about one-half that reflected by the "high-risk" curve of Figure 6. The strength scatter used to define the yield factor of safety would, of course, be the scatter in yield strength. On the basis of this crude analysis, the 1.1 factor of safety sometimes specified for yield would be quite adequate unless the scatter in yield strength is quite large. The 1.0 yield factor of safety may result in a moderately high probability of accepting a design that will experience some yield failure during operations. For instance, if the actual mean strength happens to coincide with the Limit Load, there will be a 50 percent probability that the test article will pass the test for yield strength. If such a design is accepted, there will be a 50 percent probability that the operational vehicles will experience yield at Limit. Thus,

* Gaussian distribution assumed with mean at 125 percent Limit.

a yield test to a 1.0 factor may result in a 25 percent probability of operational yield failure after successfully qualifying the design by demonstrating with one test article that there is no yield at Limit. It is suggested that a trade study be conducted on specific designs to determine the break-even yield factor of safety, balancing the cost of designing and testing to higher yield factors against the increased probability of yield failures on operational vehicles associated with lower yield factors. In the absence of such a trade study, a 1.1 yield factor of safety is recommended.

Implementation of the intent of the QSDC procedure thus far has been in the context of static or time-independent strength situations. This has traditionally been the prime strength requirement. After satisfaction of the static strength requirement, the usual procedure is to examine the structural configuration to determine whether it satisfies the requirements for time-dependent strength situations. Historically, the first time-dependent strength situation to be considered was fatigue. The intent of the QSDC Procedure is the same in the fatigue situation as in the static situation where the Limit Condition is the static strength requirement, and the Limit Usage Spectrum defines the time-dependent strength requirement. Any cumulative vehicle usage which can be defined as normal and expected must have "no" failure so long as the vehicle does not exceed the defined Limit Usage Spectrum or the defined Limit Condition during the defined Service Life.

An Omega Usage Spectrum defines a usage whose probability of exceedance is greater than the complement of the desired structural reliability. An Omega Usage Spectrum may result either from excessively severe operations during the expected or specified Service Life or from the specified normal usage carried on beyond the specified Service Life to an unexpectedly long life, the Omega Service Life. "Most" of the operational structural systems should be capable of surviving an Omega Usage Spectrum.

The intent of the QSDC Procedure in time-dependent strength situations is the same whether the time dependency is the result of fatigue, thermal, corrosion, or other similar conditions. The cumulative usage history of the vehicle is the interface between the structural system and the non-structural systems. The local environments are derivatives of the vehicle usage.

The intent of the QSDC Procedure in time-dependent situations is presumably the same as that of the Present System. Both procedures aim at defining a structural system which will not experience structural failures during the life of the vehicle. However, there is a fundamental difference in the achievement of this goal. The QSDC Procedure examines the degraded or residual strength during the vehicle lifetime and determines how this affects survival of Limit and Omega Conditions. The Present System effectively ignores the strength during the Service Life and concentrates on surviving a truncated loading spectrum to some multiple of the specified service life. If this approach produces a reliable structure during the service life, it is somewhat fortuitous because the relationship between the test life and the actual strength during the service life is not considered. In the QSDC Procedure the strength during the service life is considered directly. In particular, the problem of rejecting a design which has inadequate strength during the service life is a prime consideration.

### 2.1.3 Comparison of QSDC Procedure with the Present System

The QSDC Procedure, although presented as a new design procedure, is in reality a modification of the Present System. In particular, it is a modification of the choice of the design conditions. The implementation of these conditions, their use in the design of the actual piece of hardware, is the same as that in the Present System. Despite their differences, several comparisons and contrasts may help the user to better understand the new procedure.

First, the Limit Condition of the QSDC Procedure is essentially the same as that of the Present System. However, the definition of the Limit Condition in the QSDC Procedure is based on a probability of exceedance value, whereas the definition of the Limit Condition in the Present System is deterministically based on previous experience or the engineer's judgement, or both. The objective of either definition is to make the Limit Condition the upper boundary of normal and expected operations.

Second, the Omega Condition of the QSDC Procedure is used to fulfill a single part of the dual role of the Present System's Ultimate Load. The part that the Omega Condition fulfills is to define the required overload capability of the structure. By virtue of the fixed 1.5 factor of safety, the ultimate load is higher than the Limit Load associated with the Limit Condition. The vehicle overload capability that this provides is indirect and not really a requirement that must be fulfilled. As a result, the degree of vehicle overload capability is not known. On the other hand, by specifying a discrete Omega Condition, the degree of overload capability that the design will have is known. This overload capability is insured by the use of an Omega Design and Test Factor of Safety (OTFS). In most applications, this factor equals 1.0, but if the scatter factor or the reliability required are large, the OTFS is increased according to the curves of Figure 7.

Third, the QSDC Procedure defines requirements intended explicitly to result in a structural system which is "safe" up to the Limit Condition. The Present System satisfies this "safe" requirement indirectly and with varying degrees of certainty. Situations where the system might not have the desired degree of reliability at Limit have been recognized through experience and handled by empirical requirements.

Fourth, the loads associated with the Omega Condition are not factorially related to the loads associated with the Limit Condition. In some special situations the Limit and Omega Loads may be identical, for example, when the vacuum in a tank approaches absolute zero at the Limit Condition. The vacuum in the Omega Condition will also approach zero. It should be clearly understood that the Limit and Omega Loads are determined directly from the Limit and Omega Conditions. To emphasize this relationship, it is possible for the wing bending moment in the Omega Condition to be less than the bending moment in the Limit Condition. This situation could result from nonlinearities in the wing load distribution associated with partial stall conditions.

The similarity between the QSDC Procedure and the Present System is emphasized on Table I. The major procedural differences are the addition of Omega Conditions to the design requirements and the adoption of a factor of safety that varies from one design to another. A detailed explanation of each step on Table I is presented in Section 2.2., Static Design Methodology.

TABLE I. COMPARISON OF STATIC DESIGN METHODOLOGY OF PRESENT SYSTEM AND QSDC PROCEDURE

1. PREDICT LIFETIME OPERATIONAL CONDITION SPECTRA
2. DETERMINE $\genfrac{}{}{0pt}{}{\text{LIMIT}}{\text{LIMIT AND OMEGA}}$ * CONDITIONS.
3. DETERMINE $\genfrac{}{}{0pt}{}{\text{LIMIT}}{\text{LIMIT AND OMEGA}}$ LOADS.
4. COMPUTE $\genfrac{}{}{0pt}{}{\text{LIMIT AND ULTIMATE}}{\text{LIMIT AND OMEGA}}$ DESIGN LOADS.
5. DESIGN STRUCTURE FOR DESIGN LOADS.
6. TEST STRUCTURE FOR DESIGN LOADS.
7. MONITOR LIFETIME OPERATIONAL HISTORY.
8. REDESIGN AND RETROFIT.

* WHERE THE TOP LINE REFERS TO THE PRESENT SYSTEM DESIGN METHODOLOGY AND THE BOTTOM LINE REFERS TO THE QSDC PROCEDURE DESIGN METHODOLOGY

## 2.2 Static Design Methodology

The QSDC Procedure satisfies the intention of insuring "that the structure is of sufficient strength...to perform its intended function..." through its static design methodology. The static design methodology may be summarized as a series of eight steps, listed in Table II, that describe the choice and implementation of the Limit and Omega Conditions mentioned in Section 2.2.2. Steps 1 and 2 define the Limit and Omega Conditions for design purposes. Steps 3 through 6 are concerned with the analytical determination of the design loads, the strength of the structure, and the strength tests necessary to qualify the design. Steps 7 and 8, although not directly concerned with the initial design and fabrication of the vehicle, are concerned with the effectiveness of the design in operation.

TABLE II. STATIC DESIGN METHODOLOGY OF QSDC PROCEDURE

| |
|---|
| 1. PREDICT LIFETIME OPERATIONAL CONDITION SPECTRA |
| 2. DETERMINE LIMIT AND OMEGA CONDITIONS. |
| 3. DETERMINE LIMIT AND OMEGA LOADS. |
| 4. COMPUTE LIMIT AND OMEGA DESIGN LOADS. |
| 5. DESIGN STRUCTURE FOR DESIGN LOADS. |
| 6. TEST STRUCTURE FOR DESIGN LOADS. |
| 7. MONITOR LIFETIME OPERATIONAL HISTORY. |
| 8. REDESIGN AND RETROFIT. |

### 2.2.1 Predict Lifetime Operational Condition Spectra

Aerospace systems are designed to fulfill particular program objectives. These objectives are generally embodied in a "design mission" and alternate design missions. As soon as the "design mission" is defined, a corresponding set of operational conditions are described (as in Reference 2) as phenomena, or events, that may occur at a point in time or interval thereof and are expressed in terms of physical units such as pressure, temperature, load, acceleration, attitude, rate, and flux. For example, the design mission of the Space Shuttle might be simply stated as placing 65,000 pounds of payload in orbit and re-entering the atmosphere aerodynamically. Some hypothetical operational conditions consistent with this mission might be a nominal thrust level of 800,000 pounds, a longitudinal acceleration of 35.4 feet per second squared to 218 feet per second squared and an entry velocity of 16000 feet per second at 200,000 feet. The role of the responsible engineer will be to define and predict these and other operational conditions.

The engineer must not only predict the range of operational conditions, but he must also determine the probability of exceeding each level of the condition in the range. As an example, consider the operational condition of booster thrust. The entire range of booster thrust could theoretically be zero pounds-force to an infinity of pounds-force. Defining this range in terms of probability would then permit considering a much smaller range. Assuming that it has been determined by one of the following methods, a thrust of $1 \times 10^6$ pounds will be exceeded once in one hundred vehicle lifetimes as shown on Figure 3. Similarly a thrust of $1.2 \times 10^6$ pounds-force will have been determined as exceeded once in ten thousand vehicle lifetimes, also shown on the figure. This process of assigning a probability of exceedance to every level is continued until a smooth curve can be drawn. The assignment of the probability of exceedance was made on an average vehicle lifetime basis. In defining the range of operational conditions, this convention should be adhered to so that the design condition levels used in the next section will be consistent.

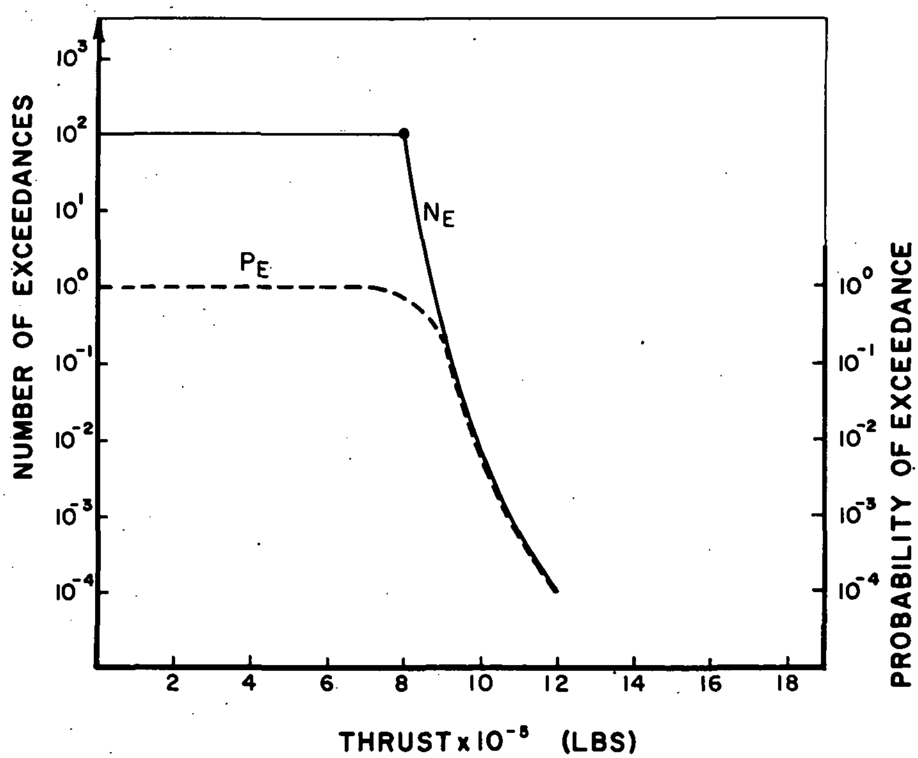


Figure 3. Number and Probability of Exceedance of the Thrust per Engine per Vehicle Lifetime (100 Missions)

Methods that can be used to assign the probability to a given condition level would be as follows: a synthesis of the condition spectrum from an analysis of the statistics of past operations with similar vehicles, an analysis of the operational capabilities of the vehicle and the performance requirements during each phase of the vehicle life, or good engineering judgement.

### 2.2.2 Determine Limit and Omega Conditions

The Limit Condition of the QSDC Procedure is a deterministic value that represents the upper boundary of normal and expected conditions for a given operational parameter. As a limit, the condition level used is a placard value that is, by decree, not to be exceeded. As such, the Limit Condition provides an administrative criteria when structural failure and operational control are considered. When structural failure below the Limit Condition occurs, the controlling agency can order the structural organization to strengthen the structure. When exceedances of the Limit Condition occur, the controlling agency can order the non-structural systems to control the operations so that future exceedances do not occur. Without a deterministic Limit Condition, such decisions cannot be made. For example, if the Limit Condition were defined in probabilistic terms, the failure or exceedance could always be attributed to the random variation. For instance, a structural failure at 90 percent of the usual Limit Condition could be attributed to a one-in-a-thousand low-strength structure, with the remainder of the structures predicted to fail above the Limit. Similarly, one occurrence of an operational condition of 120 percent of the usual Limit Condition could also be considered a random event with a one-in-ten-thousand probability but not an unacceptable one-in-ten probability. Neither of these statements can be proved or disproved. The structural failure could not be categorized as an understrength situation, nor could the operational condition be categorized as an overload. Therefore, an administrative decision on whether corrective action was needed would not be evident. Therefore, no control over the design could be exercised.

The Omega Condition in the QSDC Procedure is a deterministic value that represents the boundary between what is considered a minor overload and what is considered a gross overload. Its role in the QSDC Procedure is the definition of an acceptable overload and the absolute boundary of the strength requirement for the structural system. Basically, there is no similar condition specified in the Present System, but the Ultimate Load creates some overload capability. The Omega Condition, like the Limit, is deterministic and single valued. Although the difference between an acceptable overload and a gross overload could encompass a wide range of values, a single value is again chosen for administrative purposes. As before, specific actions concerning the structural failure and condition of exceedances can be taken by the controlling agency. Structural failure above the Omega Conditon can be attributed solely to the gross overload of the structure by the non-structural system.

In the QSDC Procedure, the choice of Limit and Omega Conditions is made on the basis of the probability of exceedance of the condition level. Thus, the Limit and Omega Conditions are two precise points in the spectra defined in Section 2.2.1. The probabilities at which these two points are defined are themselves based on the structural reliability goal proposed for the structure. Two specific equations relating the probability of exceedance of the Limit and Omega Conditions to the S.R. goal are:

$$C_L = C_n/(P_E[C_n] = \sqrt{P_E[C_\Omega]})$$

$$C_\Omega = C_n/(P_E[C_n] = 1 - SR_{goal})$$

where

$C_L$ is the Limit Condition
$C_\Omega$ is the Omega Condition
$C_n$ is the general condition that satisfies the equations
$P_E$ is the probability of exceedance and
$SR_{goal}$ is the structural reliability goal.

NOTE:

Read the Limit Condition ($C_L$) equals the variable condition level ($C_n$) such that the probability of exceeding the variable condition level ...$P_E[C_n]$ equals the square root of the probability of exceeding the Omega Condition ($C_\Omega$); also the Omega Condition equals the variable condition level ($C_n$) such that the probability of exceeding the variable condition level equals the complement of the structural reliability goal.

If all of the operational conditions can be defined in terms of their probability of exceedance, then the QSDC Procedure provides a consistent, practical, and reliable method for choosing the Limit and Omega Conditions.

The reliability level used as the basis for the particular design being considered is a management decision that is required by the QSDC Procedure. This decision is based on the mission specified for the vehicle system and the performance required of the structural system to satisfactorily complete the vehicle mission. Alternatively, the reliability level can be defined for each class of vehicle or by risk level, as on Table III. Here, a high risk level mission, such as military missions might describe, would have a structural reliability of 0.99. Such a low level of reliability is practical because of the high probability of structural failure due to hostile action and the extremes of operating conditions that the structure is subjected to in combat action. A standard risk mission, which has a corresponding structural reliability of 0.9999, would be specified by the typical space operations but could be modified as the situation warrants. Low risk missions that require a structural reliability of 0.999999 are typified by the commercial, passenger-carrying flights on commercial airlines. The above three levels of reliability are proposed because they typify the expected values of reliability desired. Precise reliability goals of 0.999998, etc., are basically not practical choices because the exact reliability of any single design can never be known. However, the reliability can be estimated fairly closely. As a result, approximate figures can be specified. If the design steps are followed properly, the reliability that the design will have should be close to the reliability specified. For example, if a 0.9999 reliability is specified, the actual reliability of the structure should be somewhere in the vicinity of 0.9999, i.e., 0.9995 to 0.99995. This is one reason why the QSDC Procedure sets reliability goals rather than reliability requirements.

TABLE III. STRUCTURAL DESIGN CRITERIA FOR STATIC DESIGN IN THE QSDC PROCEDURE

| RISK LEVEL | STRUCTURAL RELIABILITY GOAL | PROBABILITY OF EXCEEDING LIMIT CONDITION | PROBABILITY OF EXCEEDING OMEGA CONDITION |
|---|---|---|---|
| HIGH | .99 | .1 | .01 |
| STANDARD | .9999 | .01 | .0001 |
| LOW | .999999 | .001 | .000001 |

When the structure is critically loaded by a combination of operational conditions, the combined spectrum should be considered. The specification of Limit and Omega Conditions becomes more complex, but the definition remains the same. Normally, only independent operational conditions are combined; dependent conditions will need special consideration. Independent condition spectra are combined to form Limit and Omega Condition envelopes. The envelope performs the same role as the point in the single condition case: that of defining a distinct boundary. The Limit envelope is defined as the region of combined conditions less than or equal to the Limit of one or all conditions. For the two-condition case, the region is bounded by the points $0, L_1$, $L_{1+2}$, $L_2$ of Figure 4. The Limit envelope is defined by the area enclosed by lines: $\overline{OL_1}$, $\overline{L_1L_{1+2}}$, $\overline{L_2L_{1+2}}$, $\overline{L_2O}$.

The Omega envelope is defined as the region of combined conditions less than or equal to the Omega level of one and the Limit level or less of all the others for each of the conditions that are combined. For the two-condition case, the two regions bounded by $0, \Omega_1$, $\Omega_{1C}$, $L_2$ and $0$, $L_1$, $\Omega_{2C}$, $\Omega_2$ are Omega envelopes. Although the combined Omega Condition $\Omega_1\Omega_2$ is not included in the Omega envelope, sufficient strength beyond the $L_{1+2}$ point is provided when designing for points $\Omega_{1C}$ and $\Omega_{2C}$. The line $\overline{\Omega_{1C}\ \Omega_{2C}}$ is used to approximate this effect. The Omega envelope, therefore, is defined by the area bounded by the line segments $\overline{0\Omega_1}$, $\overline{\Omega_1\ \Omega_{1C}}$, $\overline{\Omega_{1C}\ \Omega_{2C}}$, $\overline{\Omega_{2C}\ \Omega_2}$, and $\overline{\Omega_2 0}$ of the figure.

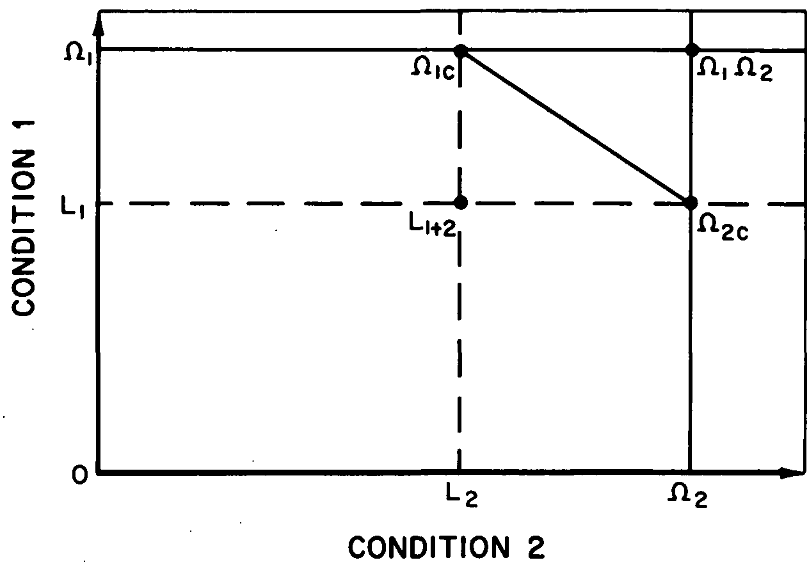


Figure 4. Limit and Omega Envelopes for Combined Conditions

When the operational condition spectra cannot be defined in terms of their probabilities of exceedance, the Limit and Omega Conditions can be chosen according to engineering judgement. The only requirement is that the definition of the Limit and Omega Conditions be satisfied by the chosen values. That is, the Limit Condition should be the upper boundary of normal and expected operations, and the Omega Condition should be greater than the worst anticipated overload. A guide that could help in assigning Omega Conditions would be the malfunctions the structure is expected to survive. Condition levels that the malfunctions would produce might be considered as minimum values for Omega.

### 2.2.3 Determine Limit and Omega Loads

The Limit and Omega Conditions define the upper bounds of the condition for two separate requirements. The Limit or Omega Load is determined as the most critical external load experienced in the condition up to and including the Limit or the Omega Condition. This investigation must be carried out with a particular component in mind. In linear systems, the Limit and Omega Loads are proportional to the magnitude of the Limit and Omega Conditions. However, nonlinearities might result from variations in aerodynamic forces, from the geometry of the structure, or from thermal effects. For instance, loads in the diagonal members of a booster engine support structure vary with the gimbal angle and peak when the thrust axis parallels the diagonal member. A typical variation might be as shown on Figure 5. In this example, choosing the load at the Limit Condition of gimbal angle would not yield the most critical load. The peak load would occur at about 50 percent of the Limit Condition. Hence, there is a need to investigate the entire spectrum of the conditions to see that the critical loads are found where nonlinearities might exist. In most cases, however, the Limit and Omega Conditions produce the critical loads.

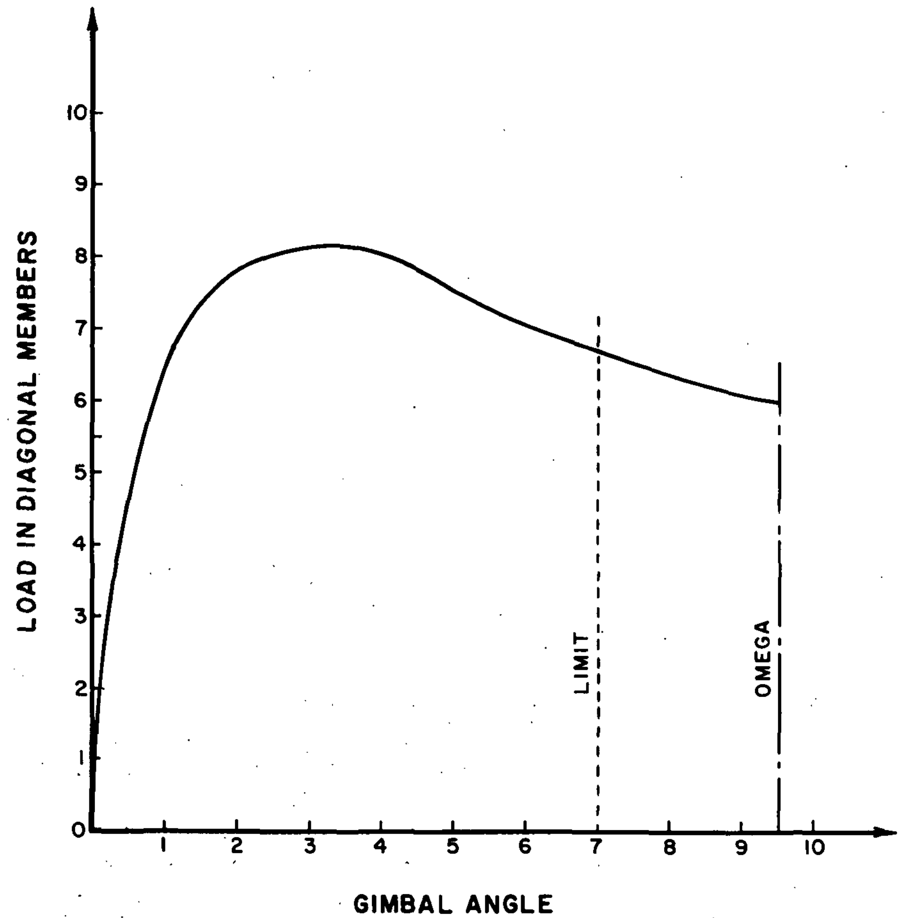


Figure 5. Hypothetical Load in the Diagonal Members of the Thrust Structure versus the Gimbal Angle

The external loads are derived from the operating conditions in the standard manner employed by the loads analysts. This particular part of the design process is not a particular concern to the QSDC other than the fact that the possibility of an error in the loads analysis may affect the reliability in service. Usually, this possible error is disclosed by the flight loads survey program. See Appendix B for a discussion of the effect of this error on the reliability in service.

The Limit and Omega Loads for the combined condition are defined as the highest loads that can be achieved within or on the Limit and Omega envelopes. Obviously, this is stretching the one-dimensional definition to two or n dimensions. As in the single condition, a full analysis of the loads for the spectrum of each condition combined with the other conditions would be required. This would yield the particular combinations of conditions that create critical external loads on the structure. The critical loads corresponding to the Limit envelope are known as the Limit Loads, and the critical loads corresponding to the Omega envelope are known as the Omega Loads.

### 2.2.4 Compute Design Loads

The Design Load for the Limit Condition and the Design Load for the Omega Condition are the loads to which the structure is sized. See Section 2.2.5. The Design Loads are the factored Limit and Omega Loads where the factor is the design and test factor of safety (TFS). Therefore, given the Limit and Omega Loads (Section 2.2.3), the Design Loads are determined by the TFS.

The design and test factor of safety (TFS) is a continuous function based on the following parameters: the scatter in structural strengths, the number of qualification tests, and the structural reliability desired. This factor of safety function is a variable, as a result, in contrast with the fixed values of safety factors used in the Present System. Without going into the details of the TFS functions (a discussion can be found in Section 3.2), Figures 6 and 7 represent the design and test factor of safety for the Limit and Omega Loads, respectively. The characteristic of the Limit Design and Test Factor of Safety (LTFS) is that it is more dependent on the strength scatter coefficient than the Omega Design and Test Factor of Safety (OTFS). For low strength scatters and all reliability levels, the OTFS is equal to 1.0. However, as the scatter increases beyond 0.06 it takes on values above 1.0 for the low risk design. For the standard risk design, the OTFS becomes greater than 1.0 when strength scatter coefficients of 0.12 are reached. The OTFS is a safety factor function performing the same type of role as the LTFS: that of insuring sufficient strength at the Omega Condition.

The computation of the Design Loads could be shown by the following example. Consider the Space Shuttle booster as the structure being designed. Assuming that the structure displays a scatter in strength of 12 percent ($\gamma_S \simeq 0.06$), the LTFS and OTFS are 1.41 and 1.0, respectively, if the standard reliability goal is used. These factors are applied to the Limit and Omega Loads of the condition being considered. Choosing the condition of thrust for this example, the Limit and Omega Loads* can be found from Figure 3 to be $1.0 \times 10^6$ pounds and $1.2 \times 10^6$ pounds, respectively. Finally, the Design Loads are computed as the product of the loads and their corresponding factor of safety:

* The condition and load for thrust are numerically the same.

| | | |
|---|---|---|
| Design Load for the Limit Condition | = | Limit Load x LTFS |
| | = | $1.0 \times 10^6$ pounds x 1.41 |
| | = | $1.41 \times 10^6$ pounds |
| Design Load for the Omega Condition | = | Omega Load x OTFS |
| | = | $1.2 \times 10^6$ pounds x 1.0 |
| | = | $1.2 \times 10^6$ pounds |

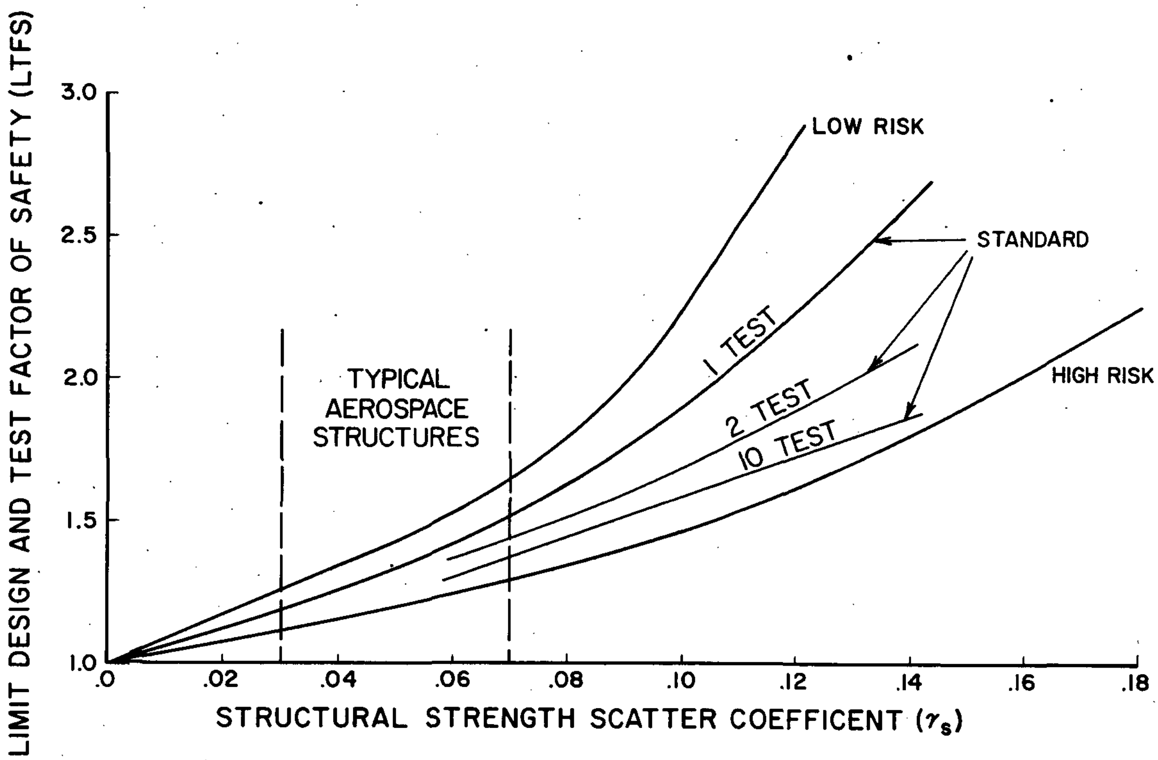


Figure 6. Limit Design and Test Factor of Safety (from Reference 1)

At the preliminary level of design, the user should not be overly concerned with the value of the predicted strength scatter. Reference 1 documents the fact that relatively large differences between the predicted and actual strength scatter will result in relatively small differences in structural reliability. As a result, the methods for estimating the strength scatter need not be extremely accurate, but they should assist the engineer in making a good approximation to the actual strength scatter. Methods for estimating the $\gamma_s$ for the design are presented in Section 3.3, and some appropriate data is presented in Section 3.4. These methods should result in strength scatters close enough to the actual so that the LTFS and OTFS chosen will produce the level of reliability desired. When the methods for predicting the component strength scatter are used, the strength scatter applied to the design of the structure is the largest scatter of the several components. The reason for this is that the qualification test will not disclose an understrength of the component with the large scatter unless the Design Load for that component is applied to it. Unfortunately, this Design Load usually cannot be applied to one element of the design without applying it to all of the elements. Thus, the component with the largest $\gamma_S$ becomes the controlling component in the choice of LTFS and OTFS and, hence, in the choice of the Design Load.

To illustrate the application of this principle, one simplified example is presented. In the example there are two members representing the multi-element structure of the wing of a shuttle or similar vehicle. Maneuvering flight in the atmosphere is the condition considered. A Limit Load Factor of 3.0 is assumed. The two-member structure consists of a lower skin in tension and an upper spar cap in compression. The strength scatter for the skin is 0.04 and that for the spar cap is 0.06. Since the critical $\gamma_S$ is 0.06, the LTFS is 1.41 (from Figure 6). The Design Load for the Limit Condition is the product of the Limit Load and the LTFS (3.0 x 1.41), namely 4.23, where the load and condition level are referred to as load factors.

If the Omega Condition corresponds to a load factor of 4.0 and the OTFS read from Figure 7 is 1.0, the Design Load for the Omega Condition is 1.0 x 4.0, or 4.0. It is a basic part of the QSDC methodology that the Limit and Omega Conditions and the corresponding Design Loads should be determined separately and carried through the analysis and test separately unless it is obvious that one or the other is the more critical. In this example, it is apparent that the Limit Design Load is the more critical.

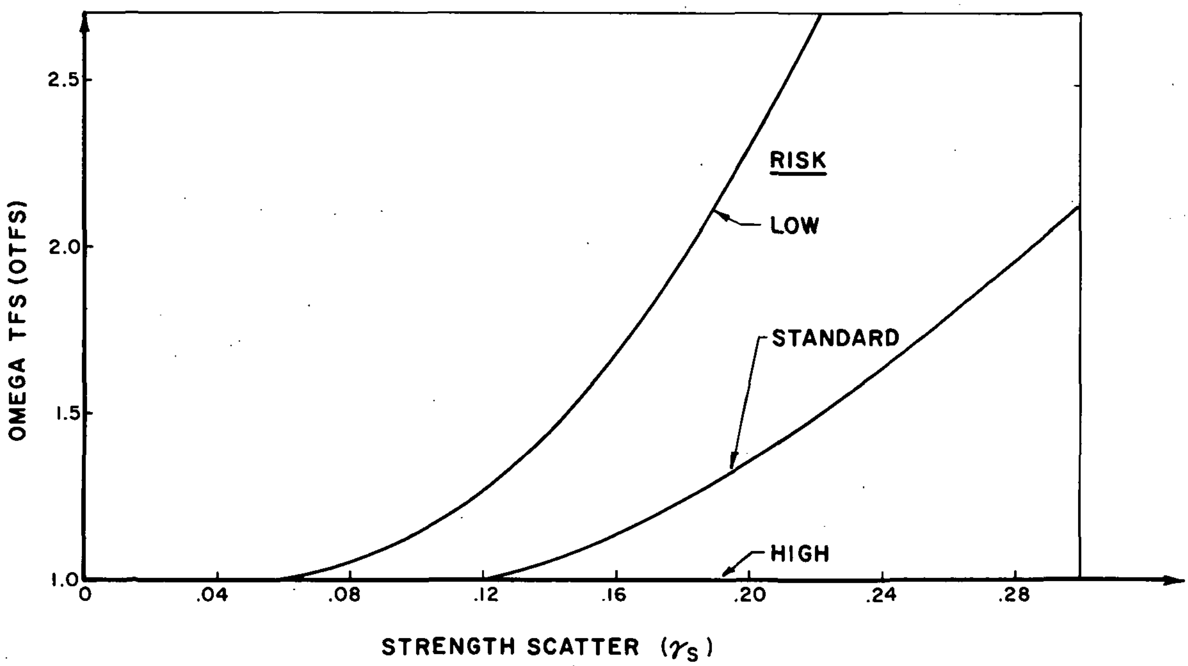


Figure 7. Omega Design and Test Factor of Safety (from Reference 1)

2.2.5 Design Structure for Design Loads

From this step forward the QSDC Procedure is essentially the same as that for the Present System. For all practical purposes, the designers, stress analysts, and test engineers will function as they always have. The structure is designed or sized at the component or element level by matching the material allowable or component strength to the critical Design Load for the condition under consideration. In other words, the structure must be sized so that the margins of safety are positive, just as required for designs in the Present System.

If both the wing skin and spar cap of the previous example are designed with zero or positive margins, the strength distributions of the components would be as shown on Figure 8. The LTFS of the wing spar cap would define the design and test load because of the larger strength scatter. Because the $\gamma_S$ of the wing skin is less in the example, the "safe" load can be closer to the design and test load as shown in Figure 8.

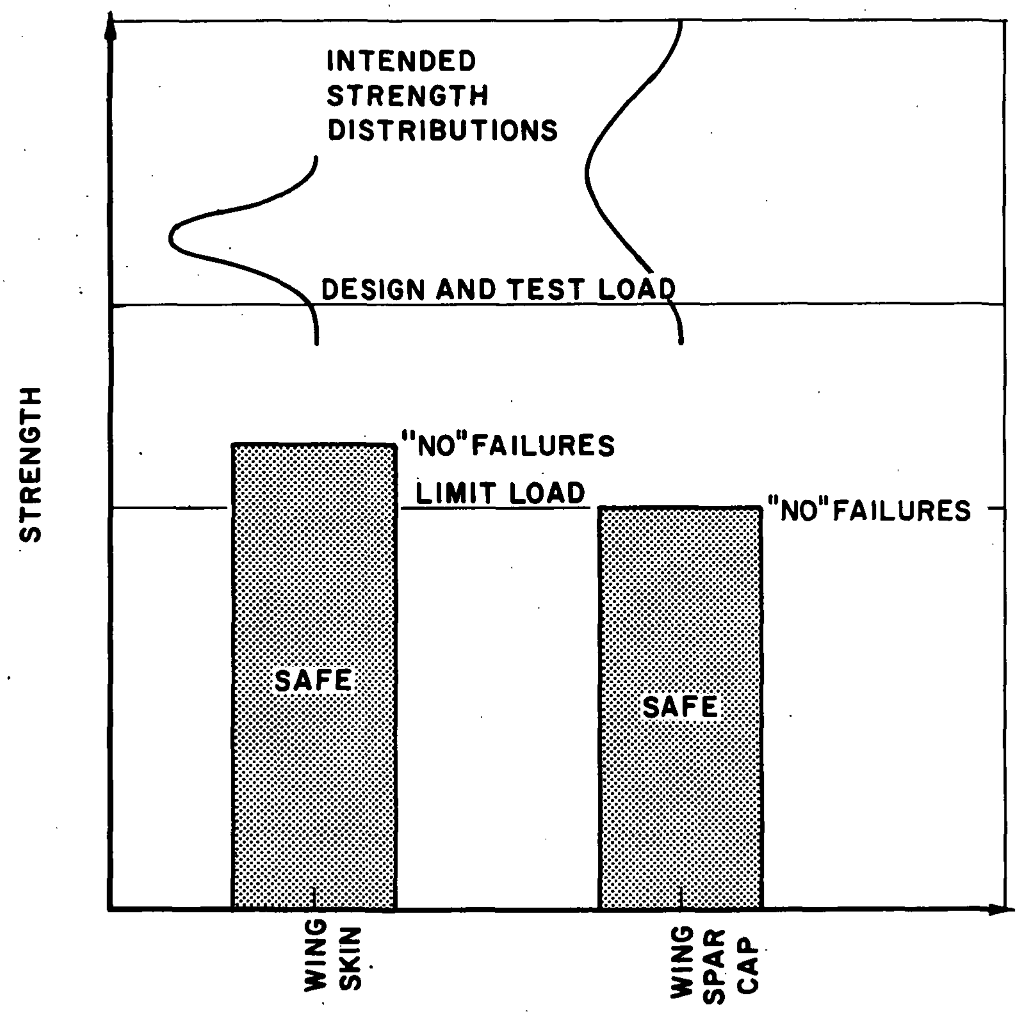


Figure 8. Design Load Defined by the Larger Strength Scatter of Several Components

In some structural systems it might be possible to test the skin separately to a lower load than that for the spar cap. Such tests must be made with caution. If separate tests and test articles are established, there is danger that the test articles may not be representative of the production vehicles because errors in the drawings and specifications of the production articles may not be duplicated in the test article. Also, a test of anything less than the full-scale structure with all of its components may not disclose errors in the internal distribution of the external loads to the various subcomponents.

### 2.2.6 Test Structure to Design Loads

After the complete structure has been sized, as indicated in Section 2.2.5, the strength is verified by static testing the full scale structure to the Design Loads. This test discloses strength errors such as errors in the analytically derived internal load distributions, errors in the dimensions and call-outs on drawings, and in the fabrication, and just plain oversights in the analysis. It is assumed that there is "no error" in the external loads of the static test, because there is no way to verify them at the time. The verification of the external loads comes later from the results of a flight loads program. If the flight loads program results are found to be inconsistent (higher) than the strength tests requirements, the structure must be retested and, if necessary, redesigned to pass the new strength requirement that is derived from the higher flight loads data. A discussion of this part of the design cycle can be found in Appendix B.

Besides disclosing errors, the static test provides an absolute, positive criterion by which it can be said that the strength requirements are met. Instead of trying to accomplish the nearly impossible task of demonstrating a reliability such as 0.9999, the strength test represents a deterministic requirement that is administrable. The structure must survive in the static test to the design load without failure. Failure to survive the static test means that the structure is understrength and must be redesigned and retested. If the structure sustains the design load, the design is adequate. The design could, therefore, be put in the production phase.

Alternatives to static testing the full-scale structure to the design load would include the following:

1) High FS Design. A decision could be made not to static test at all, but to design to a higher factor of safety. This is common in civil engineering in bridge design where the articles are one of a kind. The bridge structures are designed to a requirement approximating a factor of safety of 4. Similarly, there has been thought expressed in the aerospace industry that a factor of safety of

about 3 should be applied to non-tested aerospace structures. Applying the computer program of Reference 1 to the situation of no static test and a design factor of safety of 3.0, the computer reliability is a little less than 0.999 (about 0.9986) for most values of strength scatter. However, a factor of safety of 7.6 would be necessary to obtain the probability of failure of 0.000001 at Limit that is consistent with the "standard" reliability goal of 0.9999. Thus, depending on the reliability desired for the particular design, the decision not to static test could greatly affect the design. The advantages of not statically testing the structure are that the costs associated with static testing are eliminated and there are no schedule delays that would occur if the structure were tested and failed. The disadvantage of not static testing the full-scale structure is that there is no way to disclose the possible errors in strength. If the structure is understrength, the cost of redesign and retrofitting the service vehicle (after a costly operational failure) would greatly outweigh the cost of testing and disclosing the understrength design. The use of large factors of safety, however, does not exclude the possibility of grossly understrength designs. For example, a decimal point error could result in a design which is one-tenth of its intended strength. There is no guarantee against such an eventuality and if it did occur even the 7.6 factor of safety mentioned above would be insufficient.

2) Proof Testing. By proof testing the structure up to the Limit Load levels, the structural adequacy of an individual structure for operations up to the Limit Condition can be demonstrated. This test will reject structures that are so grossly understrength that they would fail below Limit. The advantages of proof testing is that it can disclose fabrication and maintenance errors. The disadvantages of this type of testing are that design errors are not detected and the reliability of the structure is not demonstrated. Furthermore, no capability in strength beyond the Limit Load is guaranteed. Reference 1 shows that failures due to overloads beyond the Limit Condition are more likely than

understrength failures below the Limit Condition. The proof tests alone without a design qualification test is generally insufficient to establish a high level of structural reliability.

3) <u>Coupon Testing</u>. This form of testing has been used to produce statistical data quickly and inexpensively for materials and environments that would be appropriate for the structure. Unfortunately, this testing method does not disclose errors that can occur in the actual full-scale structure.

4) <u>Component Testing</u>. This form of testing can disclose many of the same type of design errors that a full-scale static test can disclose. However, the component test will not reveal problem areas due to unexpected interactions between components changing the internal load distribution. Furthermore, component tests may not disclose assembly errors such as misaligned load paths. Another reason that component tests cannot assure the same degree of reliability as a full-scale test is that the component test article is likely to be fabricated from a different set of drawings than those used for the production vehicles. This introduces the possibility of a discrepancy between the two. Such errors could invalidate the component test.

5) <u>Reduced Scale Model</u>. The reduced scale model test has several drawbacks that exclude it from strong consideration. First, as a qualification test, the duplication of full-scale workmanship such as tolerances and variations in standard materials cannot be duplicated sufficiently. Second, errors may occur in either the model or full-scale drawings that could make the reduced-scale static strength test misleading.

6) <u>Multiple Full-Scale Tests</u>. This method lies at the other extreme from the no-test approach. Here, the advantages are more certainty of error disclosure and lower design factors of safety. These advantages are offset by the increased cost of testing and greater likelihood of schedule delays. The unique advantage of the QSDC Procedure is that the

advantages can be quantified and used to make tradeoffs against the cost increases and schedule delays that are possible.

### 2.2.7 Monitor Lifetime Operational History

The purpose of monitoring the lifetime operational history is to validate the choice of Limit and Omega Conditions. Also, the loads associated with the Limit and Omega Conditions can be validated through a Flight Loads Program. The Limit Loads may be measured directly, since the flight test article can be operated up to the Limit Conditions and readings of the loads can be taken from it.

Determination of the Omega load and verification of the choice of the Omega Condition will depend on the extrapolation of the available data. For example, the load spectrum developed in Section 2.2.1 may predict that 80 percent of Limit is exceeded 200 times during a lifetime of 5000 hours (per Figure 9). After 500 hours, or one-tenth of the vehicle lifetime, the 80 percent Limit value should be exceeded by only ten percent of the total number of exceedances or 20 times on the average. Particular vehicles may only exceed it 14 or 15 times while others may have exceeded it 25 or 26 times by the end of 500 hours. Nevertheless, the overall average should be 20.

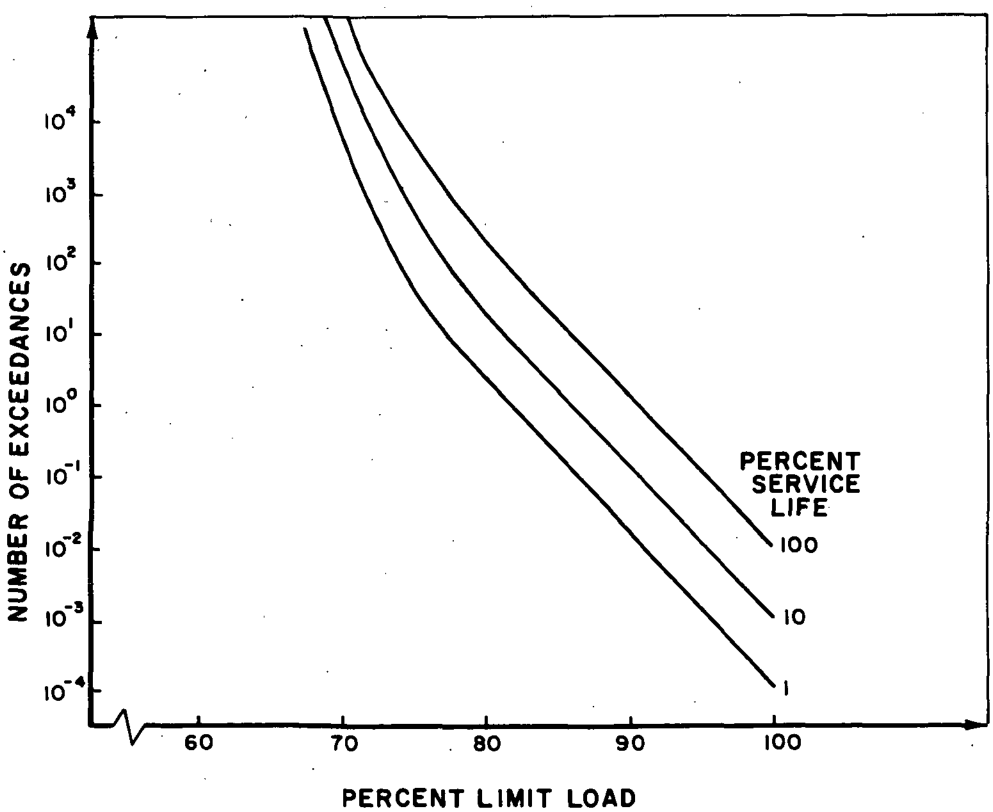


Figure 9. Number of Exceedances of Limit Load per Lifetime of the Average Vehicle (5000 hours)

Generally, if the frequency of occurrence of the conditions below the maximum operational value experienced are less than the predicted values, then the actual Omega Condition is likely to be less than that predicted. This would mean that the Omega Condition used in the design was actually more severe than necessary and that the structure was conservatively designed.

If on the other hand, the data on condition magnitudes below the maximum operational value experienced are recorded more frequently than the predicted value, say 60 exceedances in 500 hours, instead of the 20 predicted, it can be presumed that the entire spectrum is greater and that the Omega Condition will occur more frequently than predicted. Finally, the decision can be reached that the choice of the Omega Condition was insufficient and that the structure was not conservatively designed.

If the flight loads monitoring of aerospace vehicles were continued throughout the vehicles lifetime, warning systems, like the one developed in Reference 30, could be used. In brief, the warning system can be based on the number of exceedances of a given condition as in Figure 10. In order to accumulate enough exceedances for a statistically significant value, the given condition should be some percentage of the Limit, say 80 percent. This figure can be adjusted upwards as the number of hours of flight time increases. For instance, above 2000 hours, the given condition could be 90 percent Limit; and above 4000 hours, the given condition could be 95 percent Limit.

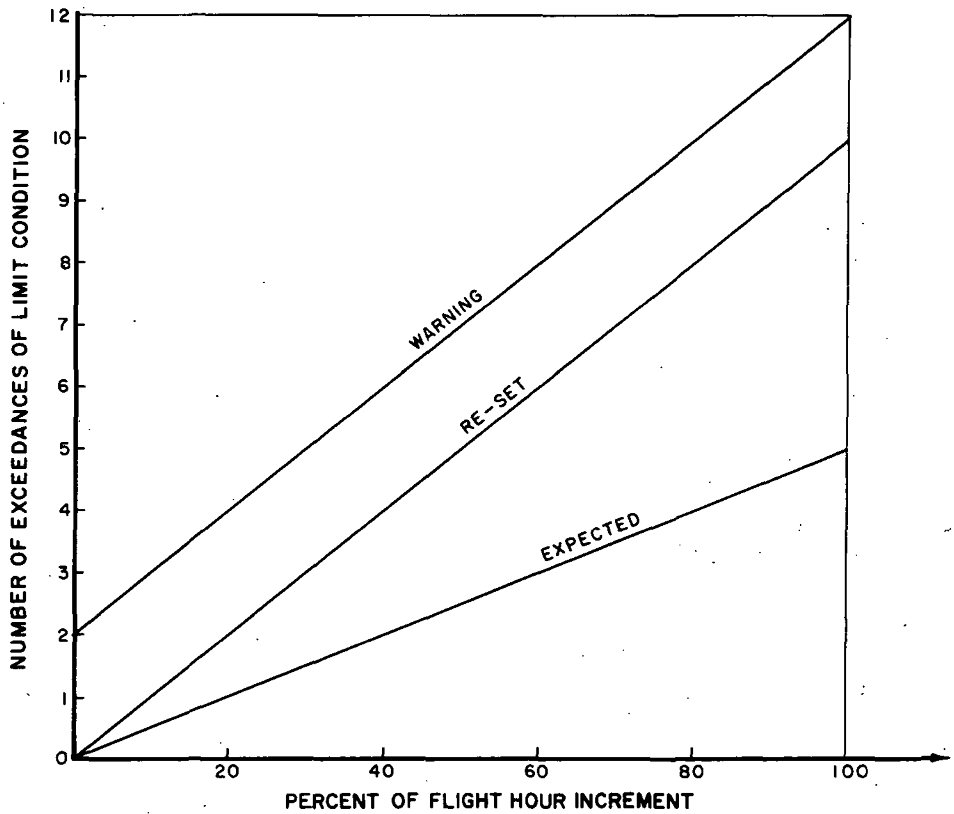


Figure 10. Warning System Mechanism for Operations Monitoring

The warning system, as part of a computerized monitoring system, prints out warning statements for excessive exceedances and excessive exceedance rates of the given condition. Whenever the number of exceedances crosses the warning line (for a specific number of flight hours), the warning system is triggered. Whenever the number of exceedances cross the re-set line in the positive direction, the program sets this exceedance as the first exceedance at the beginning of a coarser increment of flight hours. The purpose of the re-set function is to detect high exceedance rates after a long period of satisfactory service. Higher exceedance rates might be due to a change in the use of the vehicle, i.e., new mission requirements.

### 2.2.8 Redesign and Retrofit

The last step in the QSDC Procedure is the same as in the Present System. If a failure occurs at anytime during the service life of the vehicle, a decision must be made as to the cause of the failure and the required corrective action. If it is determined that the usage has been more severe than predicted so that the structure is overloaded, the problem can be solved by reducing the severity of the operational usage. If this action is not feasible, new Limit and Omega Conditions must be defined and the design process recycled. If the decision is made that the usage and loads are consistent with predicted values, the understrength must be corrected and appropriate retrofits developed and installed.

## 2.3 Time-Dependent (Fatigue) Situations

### 2.3.1 Intent

The intent of the QSDC Procedure as described in Section 2.1 is defined largely in terms of static or time-independent strength situations. At the end of Section 2.1.2, time-dependent strength situations are discussed briefly. It is noted that "the intent of the QSDC Procedure is the same in the fatigue situation as in the static situation." Specifically, the structural system should be "safe" for all operations up to the Limit Conditions and "most" of the structural systems should have overload capability to survive operations beyond the Limit Conditions up to the designated Omega Condition. It should be kept firmly in mind that no structure ever fails in fatigue because a certain number of load cycles have been imposed on the system or because a certain number of flight hours have elapsed. A failure occurs when the structural resistance to load (i.e., strength) at a given moment is less than the load at that moment. Fatigue life, as it is ordinarily defined, has nothing directly to do with the mechanistic aspects of structural failure.

The situation is illustrated in Figure 11. Two typical time-dependent residual strength distributions versus time are shown. What might be considered the distribution for a "good" design is described by curves A and B. A "bad" design is described by curves C and D. If the various individual vehicles in a fleet could be removed from service and static tested, the curves A and B might represent an envelope of the residual strengths so determined. If the operational loading environment is simulated in test by the truncated load spectrum that is used in most fatigue tests, the test article will eventually fail at the maximum load in the truncated spectrum or at some lesser load. Since the number of occurrences increases rapidly as the load goes down, the minimum load at failure is not likely to be much lower than the maximum. Thus, the range of possible loads at test failure is rather small as shown on Figure 11. The time difference between the minimum and maximum test life probably is larger than shown on Figure 11. This cannot be proved at this time since there is a lack of data to define the true scatter in life for typical structural assemblies. However, it appears that the maximum life is usually at least two to four times the minimum life rather than the 1.5 ratio shown.

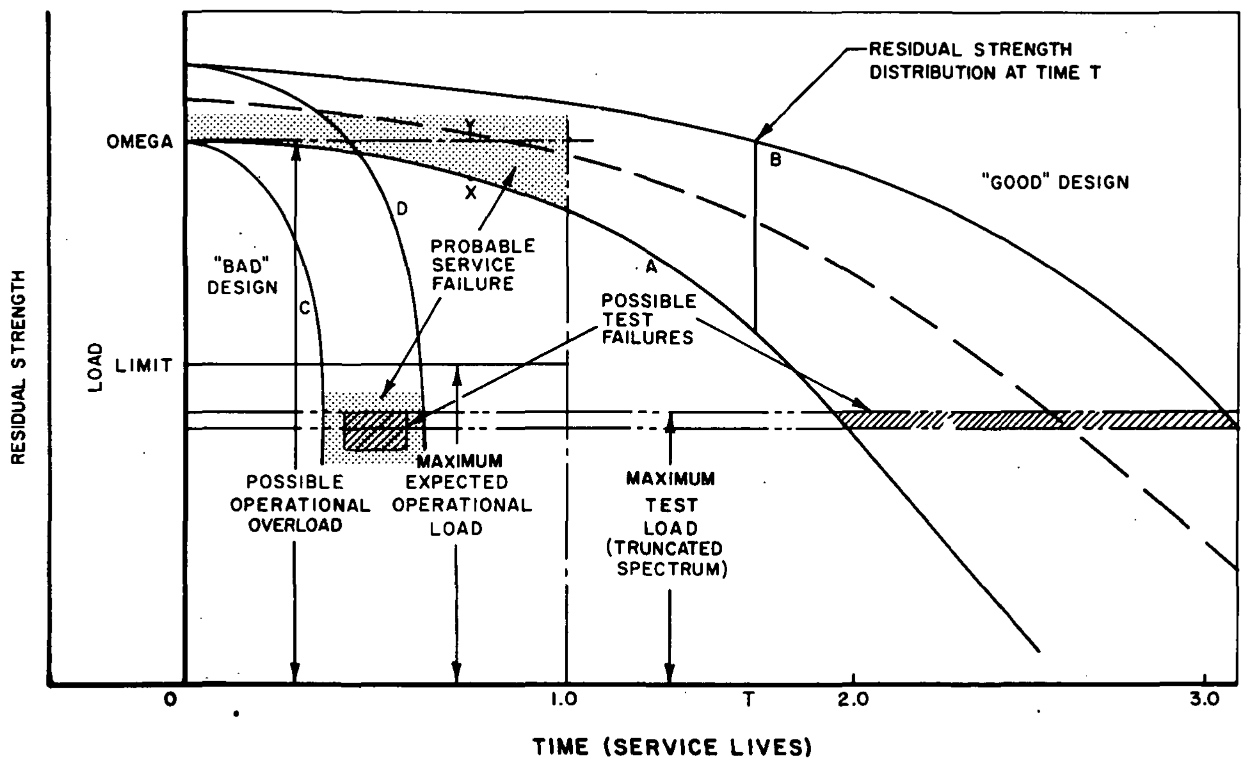


Figure 11. Time Dependency of the Fleet Strength Distribution

The residual strength distribution of the "good" design on Figure 11 portrays a situation that is likely to be marginally acceptable. If the lower boundary (99-percent-exceed) begins to move down from the Omega Load Level, the failure rate begins to increase. If the structure should be designed and tested to Omega Load in order to attain the desired static structural reliability, any decrease in residual strength below the Omega Load will result in less than the desired reliability. With a small strength degradation at the end of the service life, the change in failure rate and numbers of failures would not be obvious. All of the additional failures would occur in the region designated as "Probable Service Failures." These failures would be the result of the small fraction of the fleet vehicles which experience a gross penetration of the Limit Condition. The total number of failures would not be much above the tolerable level, but the rate of failure (number of failures per hour or 100 hours) would be significantly higher. It is stated in Reference 1 (Volume III, page 87) that a 10 percent degradation in residual strength at the end of service life would result in an increase in failure rate by a factor of 10,000. Since the choice of the Omega Condition and its relation to the static strength represents the minimum acceptable for the desired level of structural reliability, it can be understood why the degradation shown on Figure 11 is considered to be marginally acceptable.

This concept of a marginally acceptable time-dependent strength distribution does not seem to be consistent with the picture of the fatigue failure problem as envisioned by most engineers. The conventional concept of a fatigue problem is a sudden failure at a relatively low load, typically at or below the Limit Load. The "bad" design, described by curves C and D of Figure 11, is more representative of this definition of what happens when there is a fatigue failure problem. In this group of vehicles from the "bad" design, the strength of an individual vehicle would drop so fast that the probability of experiencing a load between Limit and Omega during the short time period of the strength drop would be quite small. The probability of experiencing extreme overloads during a full lifetime is rather small and the probability during a small fraction of a lifetime becomes vanishingly small. As a result, the fatigue failure for a "bad" design is most likely to occur at a load considerably below Limit. This, presumably, is the basis for the usual concept of when and at what load fatigue failures occur.

The location of test failure is likely to be within the region of probable service failures as shown on Figure 11. The region of test failure should be somewhat smaller than the region of service failures. It would be extremely difficult to detect any difference in the mode and time of test failure and the mode and time of service failure. This result reinforces the concept of fatigue failure occurring at relatively low loads and at about the same number of cycles in service as in test. This is the same concept of fatigue life that has been associated with constant-amplitude testing since the beginning of engineering studies of the fatigue problem.

The problem with conventional fatigue analysis and testing of the life in a random load environment is that it does not recognize that structural failures may occur in the region above Limit Load due to a time-dependent loss of Residual Strength.

The closer the design comes to being a "good" design the more likely the failures are to be in the high region associated with the distribution AB rather than the low region associated with distribution CD. Another part of the problem is that errors in fatigue analysis may occur as frequently or more frequently than they occur in static analysis. The Jablecki data discussed in Section 2.1.2 and the added discussion in Appendix B show the frequency of analytical error in static design. Figure 2 and the associated discussion point out how the appropriate static test can reject the under-designed systems with a high degree of certainty. The fatigue test must perform the same function as the static test as shown on Figure 2. The fatigue test must reject any unsatisfactory design with a high degree of certainty.

It is the intent of the QSDC Procedure to develop methodology which will lead to an analytical solution recognizing the interaction between a random load spectrum with occasional overloads in a fleet of vehicles and the distribution of residual strength during the service life of those vehicles. Even more important, the QSDC Procedure extends the concept of error disclosure from the static to the fatigue situation. The test requirement is intended to establish test conditions that will reject all designs which do not meet the QSDC standards for a minimal loss in Residual Strength during the service lifetime.

### 2.3.2 Implementation of Intent

The implementation of the intent of the QSDC Procedure in time-dependent (Fatigue) situations starts from the same base as in the static design situation. If the intent of the QSDC Procedure is implemented properly, the resulting structural system will satisfactorily perform its function as a vehicle subsystem. The structure will be "safe" and "never" fail in the operational region up to the Limit Condition, and "most" of the structures will survive penetration into the overload region between the Limit and Omega Conditions.

In the context of the fatigue situation, the Limit Condition is represented by a Limit spectrum, a static Limit Condition (load factor or other parameter), and a Limit Service Life. The Limit Spectrum is a load spectrum whose probability of exceedance is no greater than the probability of exceeding the Limit Condition shown on Table III. The Limit Condition has the same value as defined in Section 2.2.2. The Limit Service Life is defined as the number of hours (or flights) that are expected before operations are terminated. Since each of these factors is normal and expected and permissible, any vehicle operated within bounds of these parameters should be "safe" and "never" fail.

To complete the implementation, Omega values must be established for the same three functions as for the Limit

Condition. The Omega load factor, velocity, or other single parameter is already defined in Section 2.2.2. The Omega Spectrum is like the Limit Spectrum but more severe with a probability of exceedance no greater than the probability of exceeding the Omega Condition shown on Table III. The Omega Service Life is the maximum life to which any vehicle would ever be operated. "Most" of the vehicles should survive operations to any one of the three Omega parameters provided the other two do not exceed Limit. This is analagous to the static situation discussed in Section 2.2.2 and illustrated by Figure 4. Satisfaction of the Limit and Omega requirements in the fatigue situation is not as straightforward as in the static situation as discussed in Section 2.2. The principal obstacle is that analytical techniques for predicting the lifetime distribution of Residual Strength are not well developed. However, it should be recognized that present methodology, utilizing Miner's Fraction to predict life and validating that prediction by testing to a multiple of the specified service life using a truncated load spectrum, does not solve the problem directly, either. What success has been achieved with the present approach has been due to the indirect relation between the life distribution of test failures and the probable distribution of service failures as shown on Figure 11. Only when the resulting strength approximates curve AB on Figure 11 will the design be considered as being "good." Since the residual strength is not determined or even calculated directly, there is no guarantee that a 2X or 4X "life" will result in the required high level of strength during the specified service life. The high incidence of fatigue failures in aircraft operations in recent years does not foster great confidence that the desired results are being achieved by present methods. It is suggested that the hardware contractor for the space shuttle be required to define how he plans to develop a satisfactory lifetime Residual Strength for the shuttle or other space vehicles.

In Reference 1 (Volume II, Section 2.4) one approach to the direct solution of the fatigue reliability problem is presented. An assumption is made that the relationship between hours in service life and residual strength is defined by the relationship

$$KT = \log_e \frac{\text{Ultimate Strength}}{\text{Residual Strength}}$$

where T is the number of operational hours and K is a constant dependent on the structural configuration and loading history. This relationship permits the calculation of the structural reliability resulting from designing and testing to various multiples of the specified service life. Figure 12 shows the life multiple required as a function of the number of tests. The procedure is very analagous to that described for the static situation in Sections 2.2.4 and 2.2.6. In both the static and fatigue cases, passing the prescribed test insures that "bad" designs will be rejected with a high degree of certainty. The "good" designs that pass the test will have a high strength initially as shown on Figure 2 and will retain that strength during the service lifetime as shown on Figure 11.

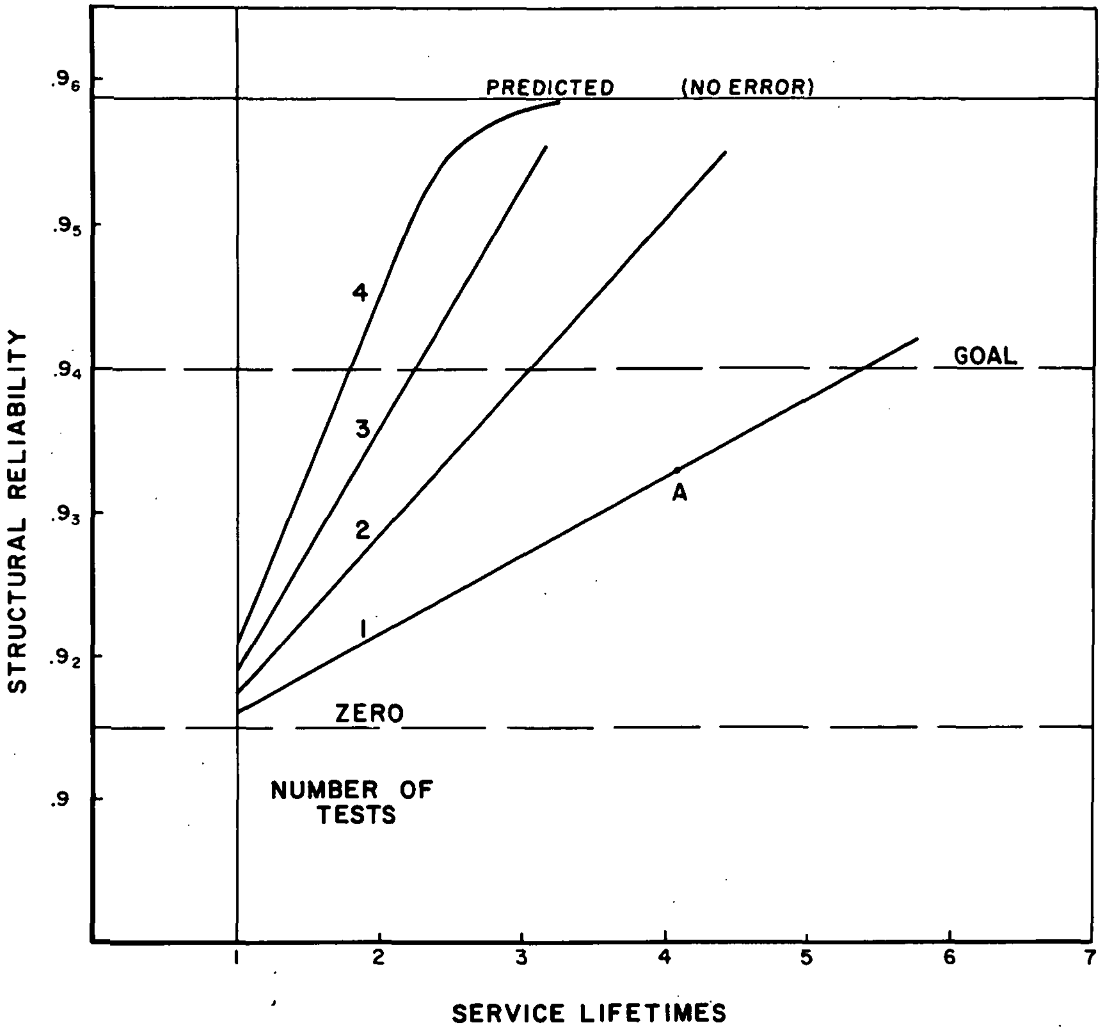


Figure 12. Structural Reliability of the Design for Various Numbers of Fatigue Tests and Multiples of the Service Lifetime (from Reference 1)

Because the QSDC procedure is strength-oriented, the fatigue test procedure can be modified by conducting a static test to the same design load required in Section 2.2.6. As shown on Figure 13, this alternate test requirement may shorten the fatigue testing time at the expense of conducting an additional static test.

It should be noted that the curves of Figures 12 and 13 are based on the "standard" vehicle with a structural reliability goal of 0.9999 as identified on Table III. If another reliability goal is chosen, the curves on Figures 12 and 13 must be recalculated by the method of Reference 1 (Volume III, Section III).

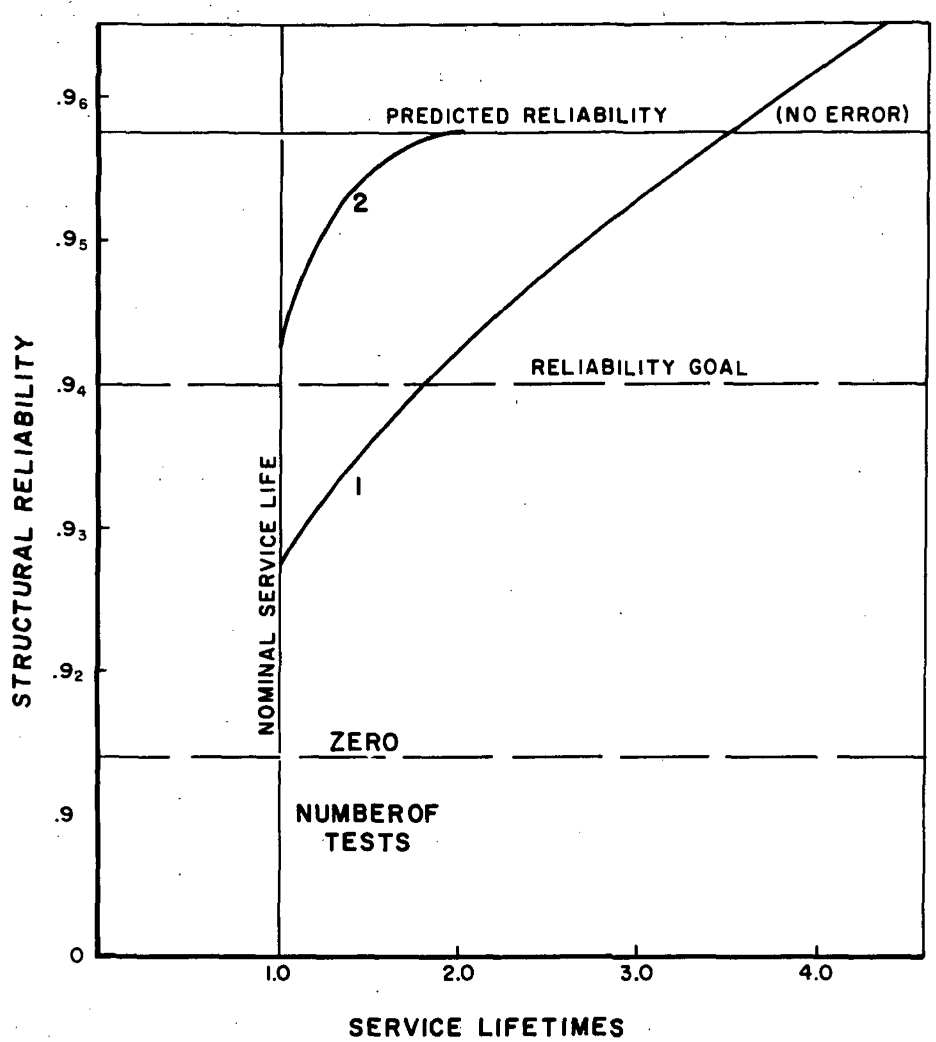


Figure 13. Structural Reliability of the Design for a Fatigue Test to the End of the Service Life Followed by a Static Test (from Reference 1).

It is believed that the requirements defined by Figures 12 and 13 are reasonable and justifiable. However, it should be kept in mind that there are two major assumptions involved in formulating the curves of Figures 12 and 13. The first is that the scatter in life (defined as the ratio of the $2\sigma$ or maximum life to the mean life) is assumed to be 4 to 1. This appears to be realistic and slightly conservative on the basis of the limited amount of test data available at present. In the same manner that the LTFS and OTFS factors for static strength (Figures 6 and 7) vary with strength scatter, the life multiple defined for the fatigue design and test requirements will vary. Figures 12 and 13 may be modified for shuttle design if substantiating data on the life scatter is available.

The other major assumption is that the shape of the Residual Strength curve is defined by

$$KT = \log_e \frac{\text{Ultimate Strength}}{\text{Residual Strength}}$$

This definition of the basic shape of the Residual Strength function appears to be reasonable for correlating the transition from initial strength to the strength at failure at the end of the typical fatigue test. It is known that in some situations the strength degradation is delayed as a result of the time required for crack nucleation. In such cases the Residual Strength curve approaches a rectangular shape with a precipitous drop in strength preceding the final rupture of the material. If such is the case, the logarithmic decrement in strength assumed in the formulation of Figures 12 and 13 will be conservative.

It is strongly recommended that any approach to the time-dependent strength problem that is less conservative than that recommended in this section of the QSDC Procedure be examined carefully and judiciously. In any event, the approach should consider (1) the possibility of failure during the service life at loads beyond Limit but less than the design load, (2) the possibility that the analytical determination of life is incorrect, and (3) the possibility of qualifying a design with inadequate life as the result of the random success of the test article to an unusually long fatigue life.

## 3. STRENGTH SCATTER COEFFICIENT

### 3.1 Definition

The strength scatter of a structural system, defined as the coefficient of strength variation ($\gamma_S$), is an important parameter in the QSDC Procedure. $\gamma_S$ represents the dispersion about the mean of the strength at failure of a group of nominally identical structures. Mathematically, $\gamma_S$ is the standard deviation ($\sigma$) expressed in nondimensional terms. The coefficient of variation is equal to the standard deviation divided by the mean strength ($\mu$) of the group of nominally identical structures, i.e.,

$$\gamma_S = \frac{\sigma}{\mu}$$

### 3.2 Importance of the Strength Scatter to the Design Process

Consideration of the scatter in strength of nominally identical structures is important because of the effect variations in the scatter have on the calculated reliability of the fleet of structures. If the reliability is computed from the probability of failure, the effect of the variation of the scatter can be shown by the increased probability of failure for the following three examples which are consistent except for the respective strength scatter coefficients of 0.00, 0.05, and 0.15. The choices of Limit and Omega Conditions at 100 and 150 percent are intended to be comparable to the design values of the Present System.

The three examples will illustrate that the reliability of a design (represented by a group of nominally identical structures) will decrease as the scatter in the strength of the structures increases. If the scatter is not considered as in the Present System, the actual reliability of the structure is not known. All three examples consider a structure designed by the Present System, that is, with a 1.5 factor of safety. The basis of the design is a non-dimensional design load of 100 percent. (This is referred to as the Limit Load in both the Present System and the QSDC Procedure). For the Present System, the Ultimate Load would equal 150 percent. The figure derived for the reliability of the structure is not based on the results of the computer program, but is the result of the following approximate analysis.

The reliability of the design computed by the program can be reasonably approximated by using a single strength distribution instead of the summation of strength distributions used in the program. When the strength distribution lies midway between the design load and the ultimate load, the reliability calculated closely approximates the reliability calculated by the program. The reliability is calculated by multiplying the probability of having passed the static test to the ultimate load by the probability of having a structure with a strength equal to the Limit Load. Finally, this combined probability is multiplied by the probability of exceeding the Limit Load, thus producing the probability of failure. The reliability is then the complement of the probability of failure. Performing this quick analysis on the three examples yields the following:

<u>Example 1 $\gamma_s = 0.00$</u>

In this example, as in the other two, the load distribution is assumed to be rectangular. The probability of equaling any level of load up to and including the Limit Load is one. For all values of load above the Limit, the probability of exceedance is zero. The Limit Load, as previously stated, is at 100 percent, and the ultimate load is at 150 percent. Despite the designer's attempt to place the strength distribution above the 150 percent level by matching the material allowable with the ultimate load (Present System design philosophy), the actual strength distribution of the design is located at 125 percent. Since there is no scatter in the strength of the design ($\gamma_s = 0$), the strength of each structure is at 125 percent. The probability of passing the test to 150 percent is zero. The probability of having a strength at the Limit level is also zero. The probability of exceeding the Limit Load is zero. The product of these three probabilities (the probability of failure) is zero. Therefore, the structure is 100 percent reliable. The test structure will fail the static test to 150 percent and, therefore, must be redesigned to pass a second static test. The final result will be that all of the strengths will be above 150 percent and all of the loads will be below 100 percent. The structure will still retain its absolute reliability with the added cost of the increased strength.

<u>Example 2 $\gamma_s = 0.05$</u>

The load distribution is the same as in Example 1. The location of the mean strength is again at 125 percent. The strength distribution defined by the $\gamma_s$ of 0.05 is concentrated about the 125 percent level, with only the tails of the distribution crossing the 100 percent and 150 percent levels. The ultimate load is 25 percent above the mean, and the design load is 25 percent below the mean. Given that the mean strength is at 125 percent, the size of the standard deviation ($\sigma$) can be computed from the definition of the strength scatter ($\gamma_s$):

$$\begin{aligned} \gamma_s &= \sigma/\mu \\ \sigma &= \gamma_s\mu \\ &= 0.05\ (125) \\ &= 6.25 \end{aligned}$$

The number of standard deviations, used as an indication of the probability of occurrence, is found by dividing the difference ($\Delta$) between the mean and the intended value (here 150 percent) by the size of the standard deviation:

$$n = \frac{\Delta}{\sigma}$$

$$= \frac{25}{6.25}$$

$$= 4.$$

This value for the standard deviation corresponds to a probability of occurrence of $3.17 \times 10^{-5}$. Thus, a successful strength test to 150 percent would occur once in 31,700 tests. Similarly, the occurrence of a strength equal to the Limit level is one in 31,700. The probability of this combination is about $10 \times 10^{-10}$. The probability of failure of this design would therefore be $1 \times 10^{-9}$ (the probability of exceedance of the Limit load is one.) The corresponding reliability of the design would be the complement of this probability of failure or 0.999999999. The significance of this result is that the chance of an operational failure at a Limit Condition after a test article passes a test to 150 percent of Limit is about one in one billion. This possibility is so near zero that any structural system can be considered "safe" in operation up to Limit after the design is qualified by a successful test to 150 percent of Limit.

Thus, a "safe" structural system results from compliance with the deterministic requirements of the Present System apparently without any probabilistic considerations. However, this desired result is dependent on the strength scatter being relatively low. In the next example it is shown that the same procedure will not result in safe structure when the scatter is large.

<u>Example 3 $\gamma_s = 0.15$</u>

As in Examples 1 and 2, the mean strength is at 125 percent and the load distribution is the same. The standard deviation ($\sigma$) in this example is:

$$\sigma = \gamma_s \mu$$
$$= .15\ (125)$$
$$= 18.75$$

The number of standard deviations (n) is:

$$n = \frac{\Delta}{\sigma}$$

$$= \frac{25}{18.75}$$

$$= 1.33$$

The probability of passing the static test to the ultimate load is 0.0918. Similarly, the probability of having a strength at the Limit Level is 0.0918. Since the probability of exceeding the Limit Load is one, the probability of failure is 0.00843. The corresponding reliability is therefore 0.9916. The reduction in reliability with this variation in strength is very large: from 0.999999999 to about 0.99.

It is very dubious that the vehicle user would consider the vehicle to be "safe" if the chance of catastrophic failure at Limit were one in one hundred. This change from safe to unsafe structure has not been a serious problem in the past because structural systems with large strength scatters were avoided by empirical means. Such things as brittle materials, long slender columns, very hot structure, and welds in tension were banned. In recent years every one of the ground rules resulting in narrow-scatter structural systems has been abandoned in the quest for higher performance in structural systems. As a result, large-scatter structural systems are no longer uncommon.

The QSDC Procedure considers this effect of the strength scatter. It places the choice of design factors on the basis of a desired structural reliability goal and the scatter in strength of the design. In this manner, a consistent level of reliability is maintained.

### 3.3 Estimation of the Strength Scatter

Having defined the strength scatter and its role in the QSDC design Procedure, the estimation of values of strength scatter to be used in the design of a structure is now discussed. The strength scatter must be estimated so that design factors can be assigned to the structure and structural components. As discussed in Section 2.2.4, the strength scatter of the component with the highest strength scatter is used to define the design factors. The methods of this section are expected to produce values of strength scatter that will estimate the actual strength scatter of the component considered with a satisfactory degree of accuracy.

It should be noted at the outset that there is, generally, insufficient data on which to base a purely statistical estimation of the strength scatter of any given component. The major amount of data with statistically significant sample sizes can be found only among material property tests. Most of the data dealing with component strength scatters have barely enough samples to permit considering the resulting scatter values statistically. This deficiency points to a need for more test data, but more importantly it negates any present need for a highly analytic estimation method. As more data becomes available, more refined estimating techniques will be generated. For the present, however, the following methods for estimating the strength scatter of a components are presented: a range estimation, a baseline estimation, an estimation by class, an estimation by judgement, and a preliminary analytic technique.

Whichever form is chosen to make an estimation of the strength scatter of the component and, hence, of the structure, the resulting quantity can be used with confidence. The estimation of the strength scatter, when made with reasonable engineering judgement, will either be close to the actual value of the scatter or be conservative enough when used in the QSDC Procedure to maintain the desired level of reliability. The reliability of the structure is not greatly sensitive to moderate variations in the estimation of the component strength scatter. That is, if 0.0425 is specified instead of the actual 0.0400, the reliability might only increase from say 0.9999 to 0.99994. Even with an estimate as low as 0.04 for an actual scatter ($\gamma_s$) of 0.05, the reliability figure is reduced from 0.9999 to about 0.9994. Thus, estimates of the strength scatter of the components and, hence, the strength scatter of the structural system can be made with enough confidence to permit using the estimates as the basis for setting preliminary design factors.

### 3.3.1 Range Estimation

This method of estimating the strength scatter of a component is based on the range in available test data. Essentially the observed range is equated with the expected range for the given sample size. The expected range for a given sample size is listed in the following table. The range is defined by the number (n) of standard deviations ($\sigma$).

| Sample Size | n |
|---|---|
| 5-10 | 3 |
| 10-100 | 4 |
| 100-1000 | 5 |
| 1000-10000 | 6 |
| 10000-100000 | 8 |

The observed range is merely the difference between the highest strength and the lowest strength in the test data (HI-LO).

The strength scatter, defined as the size of the standard deviation ($\sigma$), would then be the range divided by the number of standard deviations it defines, i.e.,

$$\sigma = \frac{(HI-LO)}{n}$$

The other parameter needed to define the strength scatter is the mean strength ($\mu$) which is approximated by the arithmetic average of the highest and lowest observed strengths, i.e.,

$$\mu = \frac{(HI+LO)}{2}$$

Finally the strength scatter ($\gamma_S$) is estimated by dividing the standard deviation ($\sigma$) by the mean ($\mu$), i.e.,

$$\gamma_S = \frac{\sigma}{\mu} = \frac{(HI-LO)}{n} \bigg/ \frac{(HI+LO)}{2}$$

$$= \frac{2}{n} \frac{(HI-LO)}{(HI+LO)}$$

where n is determined from the table by the sample size (the number of test articles).

### 3.3.2 Baseline Estimation

As a second method for estimating the strength scatter of structural components, deviations from a standard baseline strength scatter are considered. The baseline strength scatter is based on the ±10 percent variation about the mean value expected in normal engineering work. This nominal variation is equivalent to a $\gamma_S$ of 0.05. Deviations ($\Delta$) are considered from this baseline by the simple rule of:

$$\gamma_S = 0.05 \pm \Delta$$

where the deviations ($\Delta$) are based on the following considerations concerning the strength scatter of the component. The material used should be the first consideration: ductile materials may allow negative deviations ($\gamma_S$ less than 0.05), whereas brittle materials would require positive deviations ($\gamma_S$ above 0.05). Notch sensitivity could be an important parameter here. As a second consideration, material processes may need investigation. Standard, well-controlled techniques such as rolling and extrusions would produce negative deviations (low $\gamma_S$), and less precise methods, such as castings, will produce positive deviations (high $\gamma_S$). A third consideration, structural elements, such as honeycomb and waffle, will result in positive deviations (high $\gamma_S$), whereas fasteners and rivets display a negative deviation (low $\gamma_S$). Finally, fabrication techniques may need consideration. Standard joint and close tolerances exhibit negative deviations (low $\gamma_S$), whereas welds, bonding, and large tolerances do not ($\gamma_S$ high).

### 3.3.3 Estimation by Class

A third method of estimating the strength scatter was suggested by the author in a study contract for NASA (Reference 7). This method consists of dividing structures into four classes as in Table IV. A range of $\gamma_S$ is proposed for each class, and a typical structural form is indicated. If the designer chooses the maximum strength scatter in any given class for a particular design, the design will be conservative. If the designer wishes to decrease the $\gamma_S$ below the maximum for the particular design group, justification of the choice of $\gamma_S$ should be made.

## TABLE IV. STRENGTH SCATTER VALUES BASED ON STRUCTURAL CLASSES

| Class | Description |
|---|---|
| A | These structures are of high-quality, conventional construction for which, from years of experience, small variation in strength can be expected. This class will include conventional structure with high ductility materials, riveted or bolted construction at moderate temperatures, etc. The upper limit of $\gamma_S$ for this class is arbitrarily set at 0.04. |
| B | These structures include those for which a slightly higher $\gamma_S$ may be expected than for Class A structures. In this class will fall high-quality welded and bonded structures and those that fail in a simple buckling mode. The upper limit of $\gamma_S$ for this class is arbitrarily set at 0.09. |
| C | These structures have a larger variation in strength than those in Classes A and B, but are of a quality which may be used occasionally in primary structure. Most high-quality casting and structures that fail in buckling probably fall in this category. The upper limit of $\gamma_S$ for this class is arbitrarily set at 0.125. |
| D | All structures having $\gamma_S > 0.125$ are considered to fall in Class D. Most brittle structures and shells that buckle catastrophically under external pressure probably would be classified as Class D. |

A factor that may justify the choice of a lower $\gamma_S$ may be the use of enough static tests for a statistical value of strength scatter.

### 3.3.4 Judgement Estimation

Another form of estimating the strength scatter could be derived from the preliminary estimates of Figure 14. Shown here are values of $\gamma_S$ that are expected to be reasonable for preliminary design work and are based on engineering judgement. The estimates are made at three different levels: materials, structural elements, and built-up structure. The strength scatters of the built-up structure can be used as they are or they can be adjusted to reflect the knowledge of the designer on the particular configuration being considered. Although the strength scatter for structural elements may stand by itself, it should be combined with other appropriate factors by the methods discussed in Section 3.3.5. The material $\gamma_S$ should not represent the structure; rather it must be combined with other appropriate factors to produce a component $\gamma_S$.

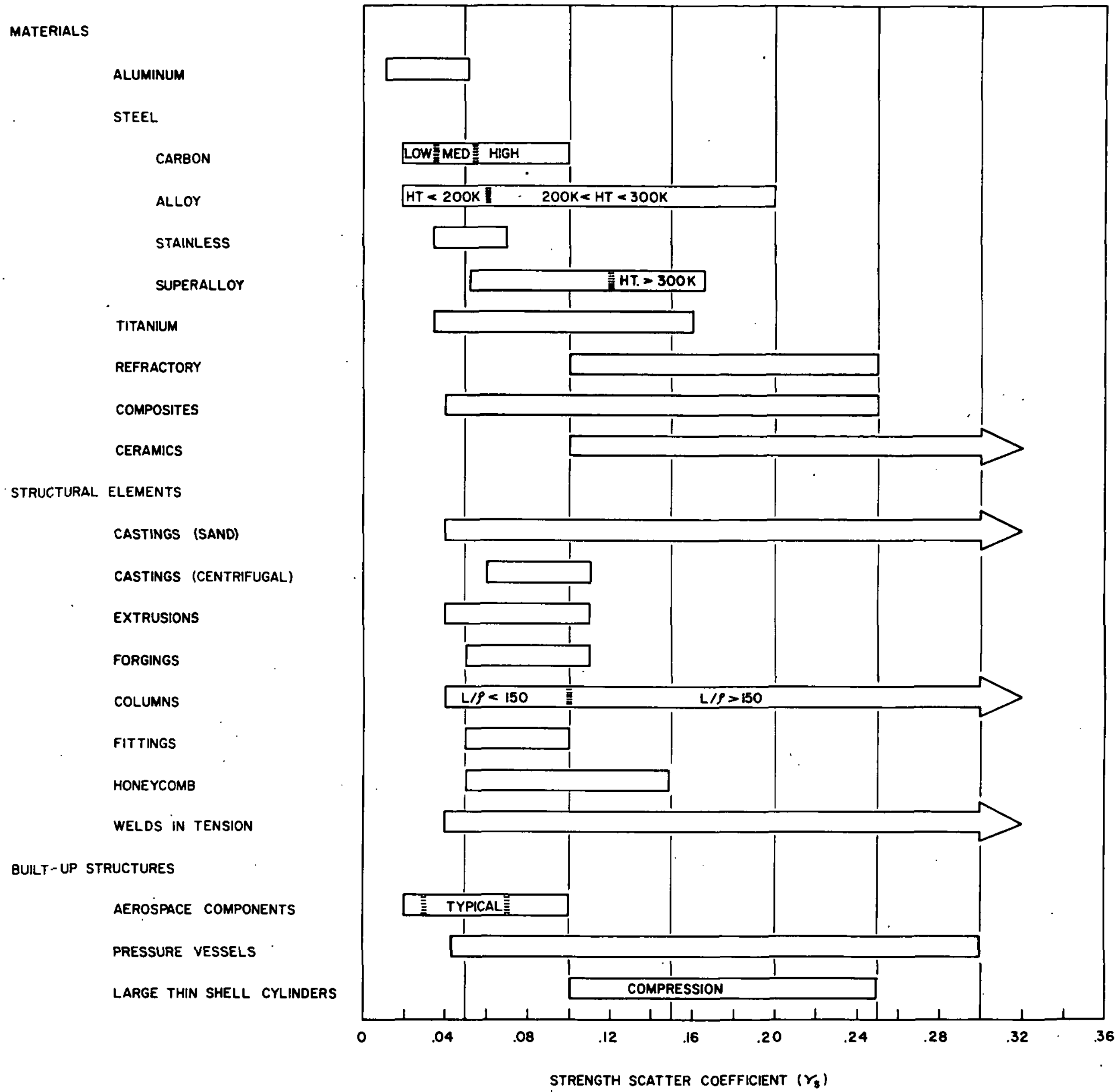


Figure 14. Typical Values of the Strength Scatter

### 3.3.5 Preliminary Analytical Technique

The strength scatter of structural components may also be derived by analytically combining several factors. That is, the component strength scatter can be synthesized from the consideration of the individual factors that contribute to it. Such factors might be the variation in material properties ($\gamma_{S_M}$), the variation in dimensions ($\gamma_{S_D}$), and the variation in the configuration and fabrication of the component ($\gamma_{S_F}$).

The combinatory rule for the component strength scatter is the square root of the sum of the squares; i.e.,

$$\gamma_{S_C} = \sqrt{\gamma_{SM}^2 + \gamma_{SD}^2 + \gamma_{SF}^2}$$

for normally distributed variables.

The combination of two strength scatter factors, the basic material strength scatter ($\gamma_{SM}$) and the configuration and fabrication strength scatter ($\gamma_{SF}$), is shown graphically in Figure 15. Several points can be quickly illustrated. First, the gray region represents the ordinary values expected for the component strength scatter. The region centers on a $\gamma_S$ of 0.05. Second, the dominance of one strength scatter factor greatly in excess of the other strength scatter factors is readily apparent. At point B, the configuration and fabrication strength scatter is greatly in excess of the basic material strength scatter, being equal to 0.20 and 0.04, respectively. By the general rule, component strength scatter ($\gamma_{SC}$) is:

$$\begin{aligned} \gamma_{SC} &= \sqrt{\gamma_{SM}^2 + \gamma_{SF}^2} \\ &= \sqrt{(0.04)^2 + (0.20)^2} \\ &= 0.204 \end{aligned}$$

Thus, the component strength scatter is just about equal to the configuration and fabrication strength scatter. In such obvious cases, the configuration and fabrication strength scatter can be used as the component strength scatter without need for the analytic estimation. Point C also illustrates the dominance of the single strength scatter factor. In this case, the material strength scatter is dominant. The values of material strength scatter and the configuration and fabrication strength scatter are 0.20 and 0.02, respectively. The component strength scatter is:

$$\begin{aligned} \gamma_{SC} &= \sqrt{\gamma_{SF}^2 + \gamma_{SM}^2} \\ &= \sqrt{(0.02)^2 + (0.20)^2} \\ &= 0.201 \end{aligned}$$

Thus, the component strength scatter is again essentially equal to the dominating strength scatter factor.

At the present, the values of strength scatter for the factors of materials, dimensions, and configurations have not been developed. This is due to the lack of sufficient data on which to base a statistical analysis which could generate the strength scatter values needed for this type of analysis. In the meantime, however, engineering judgement can be relied on to arrive at strength scatter values to be used in the estimation.

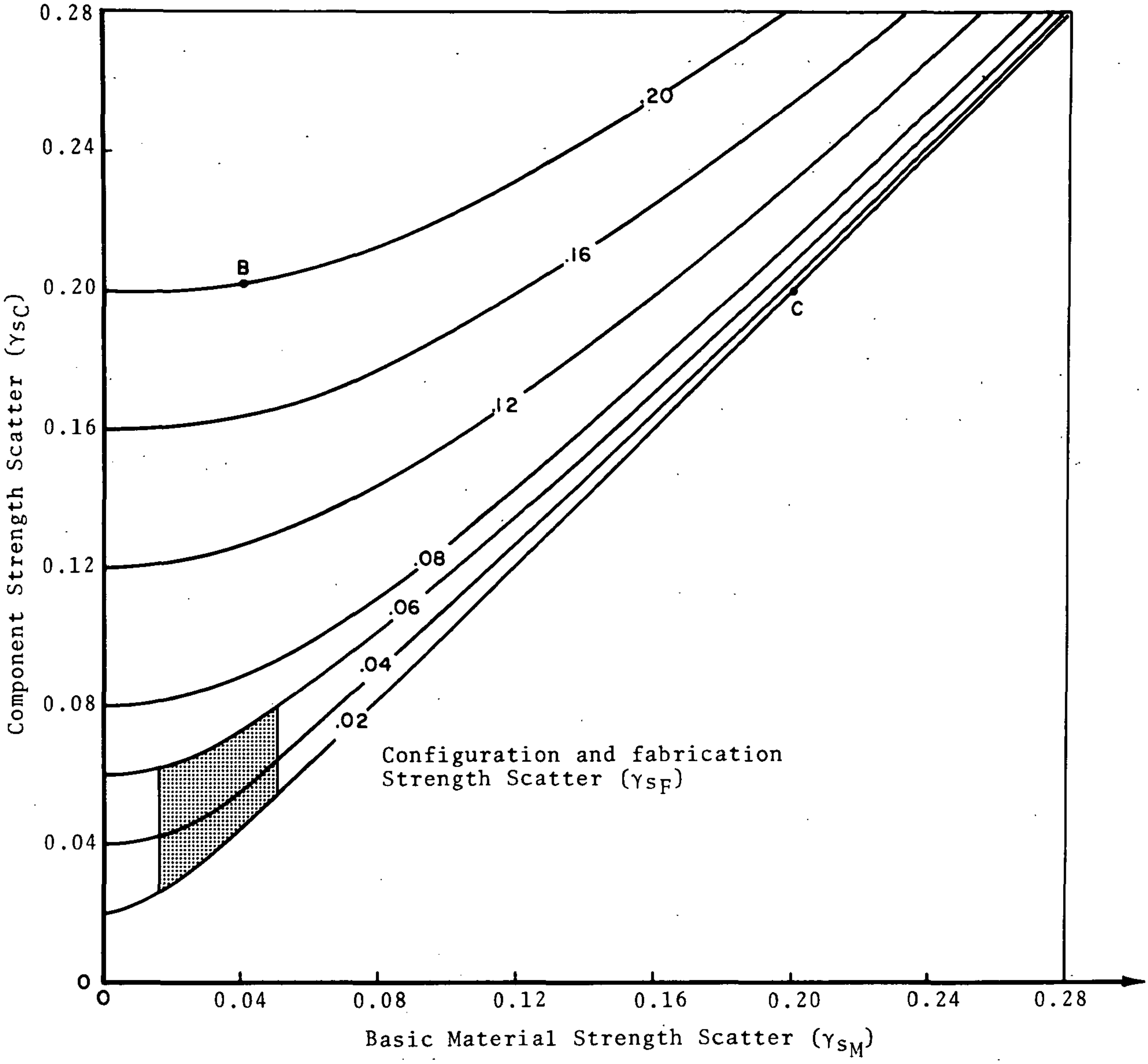


Figure 15. The Combination of Strength Scatter Factors

## 3.4 Test Data

The following tables represent the results of the literature search for strength scatter data. Unfortunately, there was very little data on the strength scatter of structures available; and structural components, generally, had insufficient data points to determine the strength scatter. The material strength scatter, however, was fairly well represented by the material property coupon tests. The major source of statistical data was Reference 8. Most of the difficulty in gathering the strength scatter data was due to the lack of sufficient information on the conditions of the test, the test specimens, and the sample size. In many instances one or the other factor was not clearly defined so that assumptions had to be made before the data was correlated.

The data reported has been arranged in three tables which parallel the main classifications of Figure 14: materials, structural elements, and structural assemblies. The strength scatter ($\gamma_S$) and the sample size (n) have been recorded, and the material, alloy, heat treatment, and form, when available, are described. When the information was not available, it was marked "unspecified."

### 3.4.1 Materials

The test data of this section are the result of coupon-type tests. That is, the data reported are generally the producer's verification of the material. These data are the type used by the MIL-HDBK-5A committee to determine the material strength allowables. In some applications these data have been used for this purpose. The data are reported for room temperatures and tensile loading unless otherwise noted. Strength scatters reported are for ultimate loads.

TABLE V. STRENGTH SCATTER DATA ON STRUCTURAL MATERIALS

| Material | Alloy | H.T. | ($\gamma_S$) | Form | n | Ref. |
|---|---|---|---|---|---|---|
| ALUMINUM | 2014 | T6 | .05 | sheet, bare | -- | 8 |
| | 2014 | T6 | .04 | sheet, bare | -- | 8 |
| | 2014 | T6 | .0507 | sheet, clad | -- | 8 |
| | 2014 | T6 | .0415 | sheet, clad | -- | 8 |
| | 2014 | T651 | .0264 | plate | 20 | 8 |
| | 2024 | T3 | .0403 | sheet, bare | -- | 8 |
| | 2024 | T4 | .0403 | sheet, bare | -- | 8 |
| | 2024 | T36 | .0403 | sheet, bare | -- | 8 |
| | 2024 | T3 | .0500 | sheet, clad | -- | 8 |
| | 2024 | T4 | .0400 | sheet, clad | -- | 8 |
| | 2024 | T36 | .0507 | sheet, clad | -- | 8 |
| | 2024 | T6 | .0410 | sheet, clad | -- | 9 |
| | 2024 | | .04 | sheet, clad | -- | 9 |
| | 7049 | T73 | .0653 | forging, hand | 165 | 10 |
| | 7049 | T73 | .0403 | forging, die | 72 | 10 |
| | 7075 | T6 | .0500 | sheet, bare | -- | 8 |
| | 7075 | T6 | .0496 | sheet, bare | -- | 8 |
| | 7075 | T6 | .0506 | sheet, clad | -- | 8 |
| | 7075 | T6 | .0407 | forgings | 204 | 10 |
| | 7079 | T6 | .0267 | forgings | 183 | 11 |
| | 356 | T6 | .0514 | casting | -- | 8 |
| | 356 | T6 | .0695 | | | |
| | 201 | T6 | .0279 | casting | 40 | 10 |
| | 201 | T7 | .0262 | casting | 40 | 10 |
| | 201 | T43 | .0312 | casting | 40 | 10 |
| | 7075 | T6 | .034 | extrusion | -- | 9 |
| | Unspecified | | .01-.05 | bar, extrusion | 5500 | 12 |
| | Unspecified | | .01-.05 | sheet | 950 | 12 |
| | Unspecified | | .03 | tube | 60 | 12 |
| | Unspecified | | .05-.17 | casting | 680 | 12 |
| | Unspecified | | .0653 | forging | -- | 10 |
| STEEL | 1035 | | .0610 | bar | 913 | 8 |
| Low Carbon | 1018 | | .0795 | bar | 58 | 8 |
| | 1045 | | .055 | bar | 40 | 8 |
| | 1117 | | .063 | bar | 105 | 8 |
| | 1137 | | .073 | bar | 140 | 8 |

TABLE V. - Continued

| Material | Alloy | H.T. | $(\gamma_S)$ | Form | n | Ref. |
|---|---|---|---|---|---|---|
| Low Carbon | 12L14 | | .073 | bar | 64 | 8 |
| | 12L14 | | .046 | sheet | 100 | 8 |
| | 12L14 | | .034 | sheet, draw qual | 160 | 8 |
| | 12L14 | | .037 | sheet, draw qual | 170 | 8 |
| | 12L14 | | .027 | sheet, draw qual | 190 | 8 |
| | 12L14 | | .039 | sheet, killed | 120 | 8 |
| | 12L14 | | .038 | sheet, rimmed | 180 | 8 |
| | 12L14 | | .072 | sheet, rimmed | 150 | 8 |
| High Carbon | 1 | | .086 | sheet | 301 | 8 |
| | 1 | | .084 | sheet | 437 | 8 |
| | 2 | | .053 | sheet | 109 | 8 |
| | 2 | | .083 | sheet | 113 | 8 |
| | 3 | | .104 | sheet | 312 | 8 |
| | 3 | | .066 | sheet | 212 | 8 |
| | 4 | | .094 | sheet | 276 | 8 |
| | 4 | | .062 | sheet | 392 | 8 |
| | 5 | | .053 | sheet | 306 | 8 |
| | %C-%Mn | | | | | |
| | .17-.75 | | .042 | casting | 180 | 8 |
| | .17-.75 | | .041 | casting,tempered | 45 | 8 |
| | .20-1.25 | | .049 | casting | 45 | 8 |
| | .22-.65 | | .0405 | casting, annealed | 25 | 8 |
| | .24-.60 | | .049 | casting, annealed | 20 | 8 |
| | .26-.70 | | .0595 | casting | 513 | 8 |
| | .28-.70 | | .0487 | casting,tempered | 100 | 8 |
| | .30-1.50 | | .0625 | | 513 | 8 |
| | .37-.75 | | .057 | tempered | 50 | 8 |
| | .44-.70 | | .080 | | 513 | 8 |
| Stainless | 201 | | .038 | sheet & strip | 102 | 8 |
| | 301 | | .026 | | 17 | 8 |
| | 301 | | .067 | | 100 | 8 |
| | 301 | | .069 | | 182 | 8 |
| | 304 | | .034 | bars | 45 | 8 |
| | 304 | | .060 | tubing | 204 | 8 |
| | 304 | | .068 | tubing | 98 | 8 |
| Stainless | 347 | | .045 | tubing | 149 | 8 |
| | 301 | | .057-.061 | annealed | | 4 |
| | 301 | | .0599 | 1/4 hard,sheet | 489 | 10 |
| | 301 | | .0545 | 1/2 hard,sheet | 195 | 10 |
| | 301 | | .0418 | 3/4 hard,sheet | 224 | 10 |
| | 301 | | .036-.048 | 1 hard, sheet | 270 | 10 |
| | 301 | | .014 | .027 sheet | 6 | 13 |
| | 403 | | .100 | bars, rolled | 549 | 8 |
| | 403 | | .033 | | 204 | 8 |
| | 410 | | .068 | tubing | 88 | 8 |
| | 446 | | .030 | tubing | 66 | 9 |
| | 17-7PH | | .050 | sheet | 106 | 8 |
| | 17-7PH | | .070 | | 101 | 8 |
| | 17-7PH | | .070 | | 541 | 8 |
| | 17-4PH | | .024 | bar | 101 | 8 |
| | AM-350 | | .049 | sheet | 194 | 8 |
| | AM-350 | | .071 | sheet | 93 | 8 |
| | 355 | | .042 | bar | 44 | 8 |
| Super Alloy | Unspecified | | .01-.02 | bar | 50 | 12 |
| | Unspecified | | .05 | casting | 190 | 12 |
| | Unspecified | | .10 | Honeycomb PH15-7Mo core | | 4 |

# TABLE V. - Concluded

| Material | Alloy H.T. | ($\gamma_S$) | Form | n | Ref. |
|---|---|---|---|---|---|
| IRON | | | | | |
| Malleable | 35018 | .0425 | Unspecified | 159 | 8 |
| | 32510 | .052 | Unspecified | 434 | 8 |
| | 32510 | .040 | Unspecified | 785 | 8 |
| | BHN[a] | | | | |
| Pearlitic | 217-235 | .053 | Unspecified | 127 | 8 |
| | 217-235 | .053 | Unspecified | 172 | 8 |
| Pearlitic | 197-212 | .062 | Unspecified | 229 | 8 |
| | 197-212 | .043 | Unspecified | 161 | 8 |
| | 179-192 | .064 | Unspecified | 261 | 8 |
| | 163-174 | .074 | Unspecified | 143 | 8 |
| MAGNESIUM | Unspecified | .02-.04 | bar | 130 | 12 |
| | Unspecified | .07-.19 | casting | 240 | 12 |
| SUPERALLOY | Nickel | .04 | sheet | 1493 | 15 |
| | Nickel | .045 | casting | 250 | 8 |
| TITANIUM | 6A1-4V | .046 | Unspecified | 2542 | 8 |
| | 6A1-4V | .049 | Unspecified | 603 | 8 |
| | 6A1-4V | .044 | Unspecified | 318 | 8 |
| | 6A1-4V | .051 | Unspecified | 115 | 8 |
| | 5A1-2.5$S_n$ | .055 | sheet | 1640 | 8 |
| | 8A1-2Cb-1Ta | .1815 | Unspecified | 15 | 8 |
| | 8Mn | .050 | Unspecified | 113 | 8 |
| | 5A1-2.8Cr-1.2Fe | .080 | Unspecified | 377 | 8 |
| | 4A1-3Mo-1V | .043 | Unspecified | 1426 | 8 |
| | 4A1-3Mo-1V | .035 | Unspecified | 1414 | 8 |
| | 16V02.5A1 | .0425 | Unspecified | 755 | 8 |
| BERYLLIUM | Pure | .0501 | sheet | 170 | 10 |
| | | .0470 | sheet | 127 | 10 |
| | Unspecified | .093 | extrusion, tubing | | 10 |
| | CA170 | .037 | strip | 66 | 10 |
| | CA170 | .0445 | strip | 66 | 10 |
| | CA170 | .039 | strip | 80 | 10 |
| | CA170 | .042 | strip | 80 | 10 |
| | CA170 | .0421 | strip | 95 | 10 |
| | CA170 | .030 | strip | 94 | 10 |
| | CA170 | .0374 | strip | 63 | 10 |
| | CA170 | .0284 | strip | 63 | 10 |
| BERYLLIUM | CA172 | .0384 | strip | 132 | 10 |
| | CA172 | .0385 | strip | 132 | 10 |
| | CA172 | .048 | strip | 132 | 10 |
| | CA172 | .033 | strip | 131 | 10 |
| | CA172 | .0392 | strip | 132 | 10 |
| | CA172 | .0296 | strip | 129 | 10 |
| | CA172 | .0378 | strip | 132 | 10 |
| | CA172 | .0238 | strip | 131 | 10 |
| | CA175 | .0527 | strip | 92 | 10 |
| | CA175 | .0585 | strip | 92 | 10 |
| | CA175 | .0544 | strip | 95 | 10 |
| | CA175 | .0362 | strip | 95 | 10 |
| | CA172 | .05 | bar & rod | 125 | 10 |
| | CA172 | .0716 | bar & rod | 169 | 10 |
| | CA172 | .071 | bar & rod | 169 | 10 |

[a]Brinell Hardness Number

### 3.4.2 Structural Elements

The structural element represents the sub-component level of a structure. Examples of items that would fall in this category are special forgings or castings, fittings, and fabrication details. Specific examples of structural elements might be rotor hub castings made for helicopters, and examples of the fabrication details of joints would be lap or butt joints or the fabrication details of honeycomb or waffle panels. Generally, the structural element data should be representative of the user form of the material to be differentiated from the producer form of the material, such as sheet, plate, extrusion, bar, and rod. The user form of the material would be the formation of spars, ribs, longerons, fittings, honeycombs, etc.

TABLE VI. STRENGTH SCATTER DATA ON STRUCTURAL ELEMENTS

| Type | Material | $\gamma_S$ | Failure Mode | n | Ref. |
|---|---|---|---|---|---|
| JOINTS | Rivets Aluminum | .06 | shear | 1400 | 12 |
| | Steel | .06 | shear | 900 | 12 |
| | Aluminum | .07 | shear | 650 | 12 |
| | Steel | .06 | shear | 85 | 12 |
| | Sheet Aluminum | .09 | bearing tear | 1400 | 12 |
| | | .09 | bearing tear | 900 | 12 |
| | | .12 | bearing tear | 650 | 12 |
| | | .12 | bearing tear | 85 | 12 |
| FASTENERS | Steel | .02-.07 | bolt nut | 130 | 12 |
| | Steel | .02-.07 | bolt shank | 40 | 12 |
| | Steel | .006-.013 | shear | 25 | 10 |
| | Titanium | .013-.026 | shear | 10 | 10 |
| | TI-6Al-4V | .00276 | dbl shear | 15 | 10 |
| | TI-6Al-4V | .0048 | dbl shear | 15 | 10 |
| | TI-6Al-4V | .01029 | dbl shear | 15 | 10 |
| | TI-6Al-4V | .01206 | dbl shear | 15 | 10 |
| | Steel | .0376 | flush head | 95 | 10 |
| WELDS | Aluminum | .08 | sheet, weld | 240 | 12 |
| | Magnesium | .19 | sheet, weld | 400 | 12 |
| | Steel | .10 | sheet, weld | 270 | 12 |
| | Steel | .07 | sheet, weld | 120 | 12 |
| | Steel | .14 | tube, weld | 40 | 12 |

### 3.4.3 Structural Assemblies

This grouping of test data pertains to the full-scale structural components or structural subassemblies. In general, statistical data on complete full-scale structures is rare. Usually, not more than one full-scale structure is statically tested to failure, and there is little evidence that any particular design was tested at the full-scale level enough times for a good statistical data point. On the other hand, structural subassemblies or component-level tests have been conducted enough times for an estimation of the strength scatter.

TABLE VII. STRENGTH SCATTER DATA ON STRUCTURAL ASSEMBLIES

| Material | $\gamma_S$ | Description | n | Ref. |
|---|---|---|---|---|
| WOODEN | .073 | "Master" Tailplane | 60 | 12 |
| METAL | .02-.03 | "Typhoon" Tailplane | 35 | 12 |
| GLASS | .11-.29 | "Vampire" canopy pressure | 90 | 12 |
| | .07-.17 | "Vanguard", pressure | 150 | 12 |
| | .10-.16 | "TSR2" tough glass, pressure | | 12 |
| | .24 | Perspex, pressure | 30 | 12 |
| Unspecified | .017 | "Hudson" tailplane | 6 | 18 |
| Unspecified | .046 | "Whitley" tailplane, up bending | 13 | 18 |
| Unspecified | .033 | "Whitley" tailplane, down bending | 7 | 18 |
| Unspecified | .060 | "Whitley" tailplane, torsion | 21 | 18 |
| Unspecified | .045 | "Mustang" wings, bending | 5 | 18 |
| Unspecified | .081 | "F-80" tailplane, bending | 3 | 18 |
| Unspecified | .099 | "F-86D" tailplane, bending | 3 | 18 |
| Unspecified | .10 | Large thin shells, R/t = 4000 | 5 | 17 |
| Unspecified | .21 | Cylinders unpressurized | 15 | |
| Unspecified | .017-.043 | Cylinders pressurized | 15 | |

### 3.4.4 Compressive Strength Data

The following data on compressively loaded cylinders and shells, with and without pressurization and with and without stiffeners, was gathered from the references listed. Because of the variety of failure modes (FM) associated with compressive loading, the failure modes have been included in the table, where possible. Although most of these data points represent experimental data on small thin shells and cylinders, the results still illustrate the large scatters in compressive loading. Full-size structures can be expected to exhibit as large a strength scatter as these data indicate. Since geometry of the structure plays a large role in determining the strength scatter for compressive loads, the dimensions of the test specimen were noted with as much detail as possible. The strength scatter is sensitive to the sample size, and, therefore, this should be considered in using the table.

TABLE VIII. STRENGTH SCATTER DATA FOR ELEMENTS IN COMPRESSIVE LOADING

| Material | FM | $\gamma_S$ | Description | Dimensions L(in) | R/t | n | Ref. |
|---|---|---|---|---|---|---|---|
| 7075-T6 | BK | .092 | Stiffened Cylinder, Pressurized | 30 | 680 | 3 | 19 |
| 7075-T6 | BK | .071 | Stiffened Cylinder, Pressurized | 15 | 680 | 3 | 19 |
| 2S-H-18 | BK | .186 | Unstiffened Cylinder, Pressurized | 21.5 | 1750 | 3 | 20 |
| 18-8 Steel | BK | .078 | Unstiffened Cylinder, Pressurized | 21.5 | 1006 | 4 | 20 |
| 18-8 Steel | BK | .146 | Unstiffened Cylinder, Pressurized | 21.5 | 1006 | 4 | 20 |
| 18-8 Steel | BK | .138 | Unstiffened Cylinder, Pressurized | 21.5 | 1006 | 3 | 20 |
| 18-8 Steel | BK | .065 | Unstiffened Cylinder, Pressurized | 21.5 | 2734 | 6 | 20 |
| 18-8 Steel | BK | .125 | Unstiffened Cylinder, Pressurized | 9.5 | 2734 | 3 | 20 |
| 18-8 Steel | BK | .065 | Unstiffened Cylinder, Pressurized | 9.5 | 2734 | 3 | 20 |
| 18-8 Steel | BK | .055 | Unstiffened Cylinder Pressurized | 21.5 | 2734 | 7 | 20 |
| 18-8 Steel | BK | .090 | Unstiffened Cylinder, Pressurized | 21.5 | 2734 | 7 | 20 |
| 18-8 Steel | BK | .096 | Unstiffened Cylinder, Pressurized | 21.5 | 2734 | 4 | 20 |
| 18-8 Steel | BK | .133 | Unstiffened Cylinder, Pressurized | 21.5 | 2734 | 7 | 20 |

## TABLE VIII. - Concluded

| Material | FM | $\gamma_S$ | Description | Dimensions | n | Ref. |
|---|---|---|---|---|---|---|
| | | | | Z | | |
| NA | BN | .478 | Unstiffened Cylinder, Unpressurized | 330 | 4 | 21 |
| NA | BN | .445 | Unstiffened Cylinder, Unpressurized | 1350 | 6 | 21 |
| NA | BN | .635 | Unstiffened Cylinder, Unpressurized | 3000 | 3 | 21 |
| NA | BN | .485 | Unstiffened Cylinder, Unpressurized | 4000 | 3 | 21 |
| | | | | L(in) R/t | | |
| NA | BK | .05 | Spherical Shell, Honeycomb | 1450 | 3 | 22 |
| S-glass Epoxy | CF | .119 | Cylinder, helical wound | 2.0 425 | 3 | 23 |
| FRP | NA | .098 | Cylinder, honeycomb | 72 117 | 7 | 24 |
| FRP | NA | .087 | Cylinder, honeycomb | 72 117 | 4 | 24 |
| FRP | BK | .154 | Curved Panel, Cylindrical | NA | 3 | 24 |
| FRP | BK | .122 | Flat Panel, Sandwich | NA | 15 | 22 |
| | | | | t | | |
| NA | LYC | .0923 | Stiffened Cylinder | .020 | 4 | 26 |
| NA | GI | .509 | Cylinder, Waffle 0°-90° | NA | 9 | 26 |
| NA | LI | .250 | Cylinder, Waffle 0°-90° | NA | 7 | 26 |
| NA | GI | .368 | Cylinder, Waffle 45° | NA | 6 | 26 |
| NA | LI | .182 | Cylinder Waffle, 45° | NA | 6 | 26 |
| NA | GI | .333 | Stiffened Cylinder, Stringers | NA | 6 | 26 |
| | | | | t R | | |
| NA | GI | .484 | Stiffened Cylinders, T-stiffeners | .1851 459 | 6 | 26 |

| Symbol | Definition | Symbol | Definition |
|---|---|---|---|
| BK | Buckling | LYC | Local Yielding |
| BN | Bending | GI | General Instability |
| CF | Compressive Fracture | LI | Local Instability |
| NA | Information Not Available | Z | $L^2/Rt\ (1-\mu^2)^{1/2}$ |

## 4. EXAMPLES

In order to illustrate the application of the QSDC Methodology as described in Section 2 and the use of the strength scatter data compiled in Section 3, the following examples were devised. Each example is intended to demonstrate the concepts which are unique to the QSDC Methodology and perhaps puzzling to the designer accustomed to the Present System. Examples 4.1 and 4.2 illustrate the definition of design conditions, both Limit and Omega, for controllable and noncontrollable operational conditions, respectively. Example 4.3 demonstrates the use of strength scatter data in a material trade-off analysis with the QSDC Procedure. A problem of designing for an elevated temperature environment is treated in Example 4.4. Example 4.5 is concerned with design for combined conditions, utilizing the QSDC Methodology.

### 4.1 Illustration of Design Condition Definition by Operational Restriction

During the launch phase of the Space Shuttle mission, the decrease in vehicle weight due to fuel consumption would result in a continuously increasing longitudinal acceleration for a constant engine thrust. The load factor resulting from this operation would be a severe operational condition imposed on the structure. A reasonable solution to this problem is to control the thrust level to restrict the load factor to an acceptable range. Thus, an example of an operational condition that would require a restriction would be the longitudinal load factor (LLF). The restriction is necessary to optimize the structural weight. As a particular case, it is assumed that a hypothetical analysis yields a 3.0 restriction on the LLF. An illustration of the nominal longitudinal load factor versus time is shown in Figure 16. The restriction to 3.0 is shown as the solid line labeled "CONTROLLED." The dashed line labeled "UNCONTROLLED" represents the nonrestricted longitudinal load factor.

The Limit and Omega Conditions can be defined by the variation in longitudinal load factor produced by the control system. A typical control system can be expected to control the thrust so that the resulting LLF will not exceed 105 percent of the nominal 3.0 value. Only in very rare cases, such as a gross malfunction, would the thrust control system allow the LLF to exceed 120 percent of the nominal value. Assuming that the nominal value of the condition is exceeded half of the time, the three points can be used to produce a cumulative probability of exceedance curve of longitudinal load factor as in Figure 17. The terms "usually" and "almost always" can be interpreted as probabilities of 0.01 and 0.0001, respectively. These values are consistent with the levels of cumulative probability used to define the Limit and Omega Conditions for the standard $S.R._{GOAL}$ of 0.9999 (see Table III) and will be used in this hypothetical example.

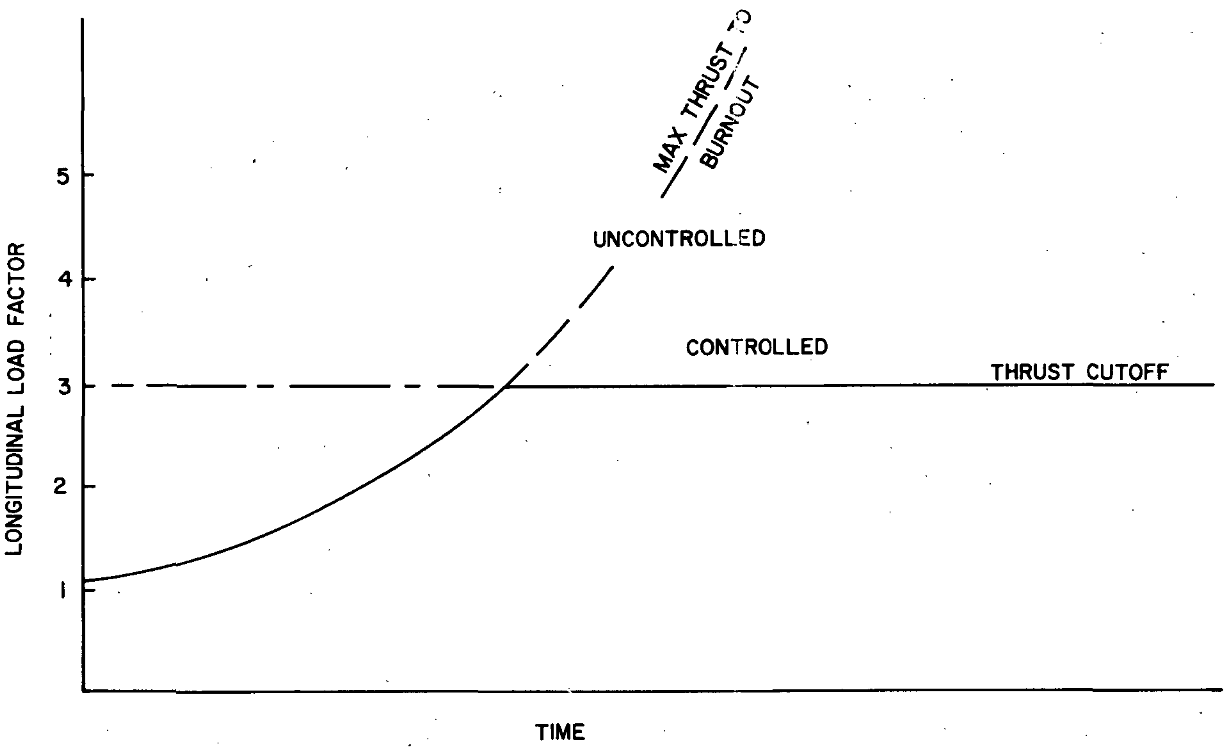


Figure 16. Typical Longitudinal Load Factor versus Time for Controlled and Uncontrolled Thrust

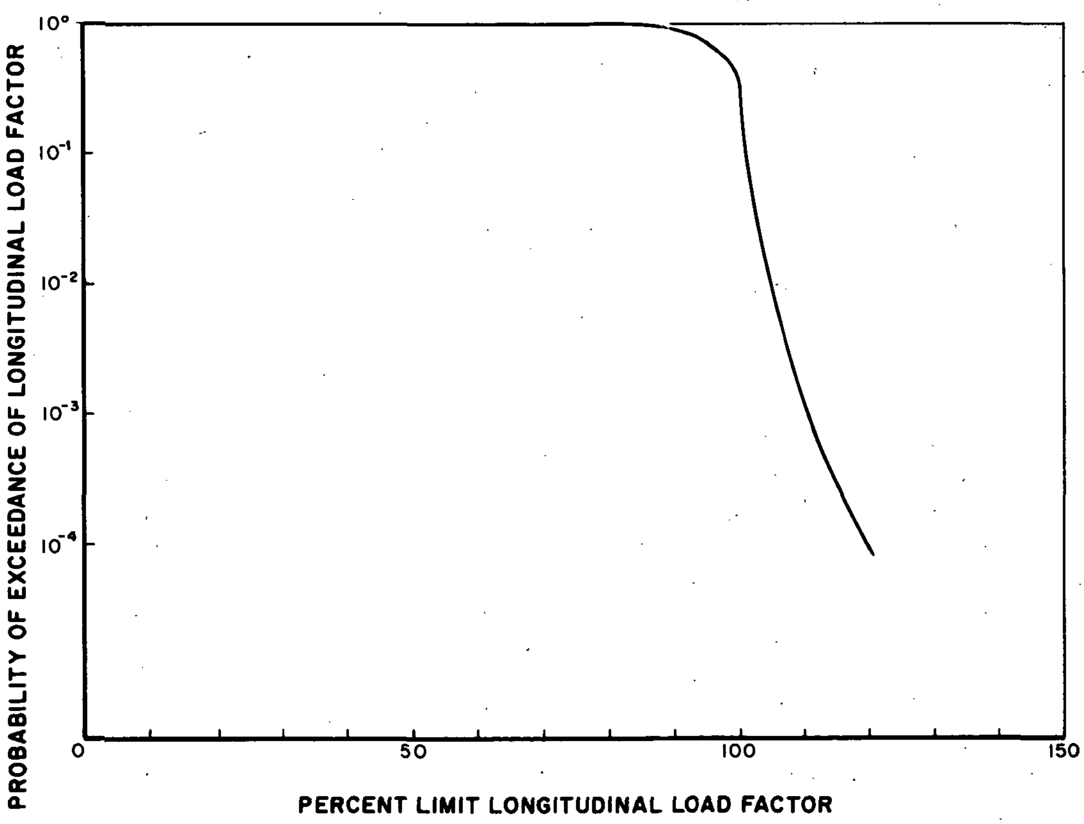


Figure 17. Typical Probability of Exceedance of Longitudinal Load Factor versus Percent Limit Longitudinal Load Factor for Controlled Thrust

Note that the Limit and Omega Conditions could be established deterministically. If the 105 percent of Limit Condition (3.15G) satisfies criteria similar to those ordinarily used in establishing Limit Conditions such as in NASA SP-8057 (Reference 2), it can be considered to meet the QSDC requirements:

(1) Qualitatively, the Limit Condition should be the upper boundary of normal and expected operational conditions.

(2) The Limit Condition should impose little, if any, limitation on operational usage during the planned mission.

(3) There should be general agreement among all concerned (structural and propulsion systems, mission planning, program manager, etc.) that any exceedance of the Limit Condition will result in an investigation to determine the cause and corrective action to prevent future exceedances.

All concerned should agree that the Omega Condition, 120 percent of the Limit value (3.6G), meet the following criteria:

(1) The Omega Condition can occur only as the result of a gross malfunction of the propulsion control system.

(2) If a catastrophic structural failure occurs at or beyond the Omega Condition, the failure will not be considered the responsibility of the structural system.

(3) The correction action for such a gross malfunction will be to modify and improve the performance and reliability of the propulsion control system.

These criteria for defining the Limit and Omega Conditions require decisions by the responsible management which can be reduced to yes or no answers. As noted, the Limit Condition is essentially the same as the traditional Limit Condition. There is no intent to change the procedures already established for defining Limit Conditions. However, more consistent Limit Conditions would result if the criteria were quantitized as shown in Table III.

Omega or overload conditions have generally not been defined in the past with the exception of some ultimate conditions, notably landing impact and crash loads. However, there has always been an implicit definition for such conditions. In the event of a catastrophic failure, an accident investigation group is usually convened to establish the "probable cause." In many cases, the probable cause resides in a nonstructural system and no corrective action is required. If no structural system has been judged responsible after the fact, it seems reasonable that the same decision can be made in advance.

The next step of the design procedure would be to determine the design and test factor of safety (TFS) for the Limit and Omega Conditions. From Figures 6 and 7 the LTFS and OTFS for the condition can be found according to the scatter in structural strength. The booster-orbiter attachment fitting is selected as a typical structural component to illustrate this application of the QSDC Procedure. It is assumed that the attachment fitting will be a 7075-T6 aluminum forging. To simplify the problem, no elevated temperature effects are considered.

The strength scatter for a 7075-T6 forging is 0.0407 from the data in Section 3.4. Entering the curve of Figure 6 with this value for the strength scatter, a desired design structural reliability of 0.9999, and a qualification requirement of one static test yields an LTFS of 1.24. A similar use of the curve in Figure 7 gives an OTFS of 1.0.

If these factors were applied to the loads produced by the Limit and Omega Conditions (here the 3.15G and 3.60G refer to loads and not conditions), the design load of 3.90G for the Limit Condition and the design load of 3.60G for the Omega Condition would result. The more severe of the two loads, namely the 3.90G load, is chosen as the design load for the attachment fitting. This choice insures a sufficient reserve against understrength and some capability above the requirement to survive overloads.

The Present System (1.5FS) would determine the Limit Condition from the nominal value of the restricted operational condition and the variation of conditions about this nominal. The load that corresponds to the Limit Condition 3.15G is multiplied by 1.5. The resulting Ultimate Load of 4.72G is used as the design point. In comparison with the QSDC Procedure, the Present System would tend to overdesign the structure by 21 percent.

### 4.2 Illustration of Design Condition Definition for Noncontrollable Operational Conditions

Of the conditions chosen as operational conditions, those that describe the natural environment are noncontrollable. For example, the encounter of gusts in atmospheric flight is beyond the control of either the structural system or any non-structural system. The avoidance of severe thunderstorms may be a form of control, but this is only a partial control; it excludes consideration of the maximum velocity gusts. The range of average gust velocities is not avoided and such velocities form a noncontrolled operational condition. This noncontrollable condition could be contrasted with the controllable operational condition of the longitudinal load factor used in Example 4.1. In the latter, the propulsion system organization can control the thrust and thereby control the longitudinal load factor; whereas in the former no non-structural system can control the gust velocity. The structural system must provide sufficient strength to survive the Limit Condition without failure and sufficient strength for overloads. It can be shown that the Present System does not provide for overloads sufficiently by simply using the 1.5 factor of safety. In contrast, the QSDC Procedure does not depend on the factor of safety to provide for the overload capability in strength. Rather, it utilizes a specific design requirement for overloads, the Omega Condition.

To illustrate the lack of overload capability provided by the Present System, consider the design of the structure for the symmetrical, vertical gust encountered in atmospheric flight. In particular, consider the criteria set down by Reference 27 and used in Reference 2 for symmetrical vertical gusts. A criterion, the Limit Condition, for gusts is a 50 feet per second derived gust velocity ($U_{d_e}$) for the maximum level flight velocity ($V_H$). The condition, gust velocity, is converted to the vehicle response, and then interpreted in the design process as the normal load factor ($N_z$). As a load factor, the criterion for symmetrical gusts becomes a specific design requirement that can be met. For our example of a 50 feet per second gust at $V_H$, the incremental load factor due to the gust is 1.5G. The incremental load factor is linearly dependent on the gust velocity:

$$\Delta N_z = k\, U_{d_e}$$

where $k = 0.03\ (\text{ft/sec})^{-1}$ for this example. The load factor experienced in level flight (1.0G reference) would then be 2.5G for positive (up) gusts and -0.5G for negative (down) gusts. Assuming that the internal loads associated with the 2.5G load factor and -0.5G load factor can be represented by these load factor values, the ultimate loads would then be represented by the Limit Load Factors multipled by 1.5. The ultimate load for positive (up) gusts would be represented by 3.75G, and the ultimate load for negative (down) gusts would be represented by -0.75G. These loads would represent increments in load factor of +2.75G and -1.75G which are not symmetrical about the 1.0G level flight reference. Interpreting these load factors in terms of gust velocities, the ultimate loads represent gust velocities of 91.7 feet per second for positive gusts and -58.4 feet per second for negative gusts. The 1.5 factor of safety does not provide much overload capability for negative gusts, but it does provide a large overload capability for positive gusts. Although it has provided sufficient strength for the ±50 feet per second symmetrical, vertical gust as a Limit Condition, it has not provided for a symmetrical gust greater than 58.4 feet per second (with the exception of additional positive gust capability). The design problem of defining a sufficient overload would arise from having the different gust velocities of +91.7 feet per second and -58.4 feet per second for positive and negative gusts. If, on the one hand, the ±58.4 feet per second gust is sufficient as an overload condition then the design for positive gusts (+91.7 feet per second) is too severe and could be reduced. On the other hand, if the ±91.7 feet per second gust is the proper value for an overload gust condition then the structure is understrength for the negative gusts (-58.4 feet per second) and the strength should be increased.

The QSDC Procedure avoids the confusion that could result from depending on the factor of safety to provide overload capability in strength. The QSDC provides for the overload capability in strength by specifying a separate and distinct design condition for overload, the Omega Condition. Sufficient strength at this condition is insured by the Omega Design and Test Factor of Safety (OTFS) applied. The Present System provides some overload capability by applying a factor of safety (typically 1.5) to the Limit Loads. The increment in operational overload capability is indeterminate and may vary from one design to the next.

The QSDC Procedure specifies the Limit and Omega Conditions on the basis of their probability of exceedance (see Section 2.2.2, Table III). For the example of the symmetrical, vertical gust encountered in high-speed level flight, the QSDC would specify the Limit and Omega Conditions from a probability of exceedance curve, such as in Figure 18. Assuming that the booster or orbiter structures are designed for the standard reliability goal of 0.9999, the probability of exceeding the Limit and Omega Conditions would be $1 \times 10^{-2}$ and $1 \times 10^{-4}$, respectively. From the figure, the Limit Condition would be ±50 feet per second gust, as in the Present System, and the Omega Condition would be ±79 feet per second gust. The criteria, the Limit and Omega Conditions, are then interpreted in terms of normal load factor ($N_Z$), as in the Present System. The incremental load factor due to the Limit Condition is ±1.5G as before, and the incremental load factor due to the Omega Condition is ±2.37G. The load factors at high-speed level flight would be +2.5G and -0.5G for positive and negative Limit gusts and +3.37G and -1.37G for positive and negative Omega gusts, respectively. To insure sufficient strength for the Limit and Omega Conditions, the Design and Test Factors of Safety (TFS) of Figures 6 and 7 are applied to the loads on the structure. For the standard reliability goal and an assumed strength scatter for the booster or orbiter structure of 0.05, the Limit Design and Test Factor of Safety (LTFS) of Figure 6 would be 1.32. The Omega Design and Test Factor of Safety (OTFS) for the specified reliability and strength scatter would be 1.0 (see Figure 7). The booster and orbiter structure would then be designed to the most critical positive and negative loads associated with the Limit and Omega Conditions. The Design loads for the Limit Condition are the product of the Limit Loads (represented by the load factor of +2.5G and -0.5G) and the LTFS (1.32). Thus the Design Loads for the Limit Condition are 3.30G and -0.66G for the positive and negative Limit gust Conditions, respectively. The Design Loads for the Omega Condition, similarly, are the product of the Omega Loads (load factors of 3.37G and -1.37G) and the OTFS (1.0). Since the OTFS equals 1.0, the Design Load for the Omega Condition equals the Omega Load: 3.37G for positive gusts and -1.37G for negative gusts. By designing for the +3.37G and -1.37G load factors, sufficient strength is provided for the overload requirement represented by the gust condition of ±79 feet per second.

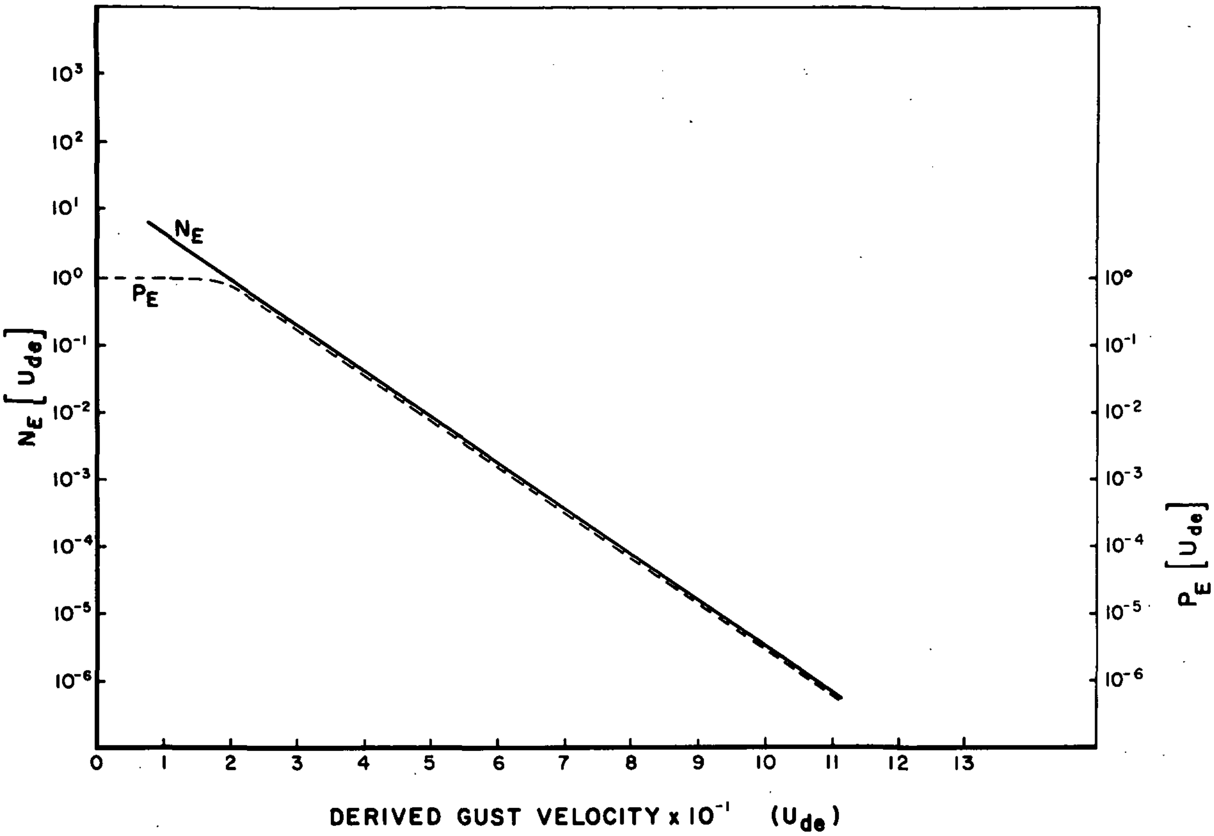


Figure 18. Typical Number and Probability of Exceedance of Gust Velocities per Mile of Flight versus Gust Velocity

In comparison, the Present System designs to a +3.75G and -0.75G load factors and thus provides sufficient strength for the understrength requirement represented by the ±50 feet per second gust. The resulting overload capability is for a +91.7 feet per second gust and a -58.4 feet per second gust, which is not truly representative of an overload requirement for symmetric gust velocities.

## 4.3 Illustration of Material Trade-Off Through the QSDC Procedure

This example will show a technique for making material trade-offs based on the strength requirements of the QSDC Procedure. The subject will be the engine support truss of the launch vehicle. For simplicity, the thrust distribution of Figure 3 is assumed. The Limit Condition is assumed as the 1:100 occurrence value in thrust, and the Omega Condition is assumed as the 1:10,000 occurrence value in thrust. From the figure, the Limit thrust is 1,000,000 pounds-force. The Omega thrust is 1,200,000 pounds-force (The choice of Limit and Omega values is based on the standard structural reliability goal (0.9999) with one static test).

The materials to be considered for trade-offs in this example are tubing of (1) steel, (2) beryllium, and (3) Lockalloy. The steel tubing used will be Type 304 in the annealed condition. From the strength scatter data of Section 3, the strength scatter coefficient for this steel tubing equals 0.060. The corresponding LTFS (from Figure 6) for the structural reliability indicated above is 1.41 and the OTFS (from Figure 7) is 1.0.

The Design Load for the Limit Condition is computed for the steel tubing:

$$\begin{aligned}\text{Design Load for Limit Condition} &= \text{LTFS} \times \text{Limit Load}\\ &= 1.41 \times 1 \times 10^6 \text{ pounds}\\ &= 1.41 \times 10^6 \text{ pounds-force}\end{aligned}$$

and the Design Load for the Omega Condition is computed:

$$\begin{aligned}\text{Design Load for Omega Condition} &= \text{OTFS} \times \text{Omega Load}\\ &= 1.0 \times 1.2 \times 10^6\\ &= 1.2 \times 10^6 \text{ pounds-force}\end{aligned}$$

Of the two Design Loads computed in the above manner, the greater load is used as the critical load; in this example the Design Load for the Limit Condition is used. (Note that this means that more strength is needed to provide a reserve against understrength than to provide a capability for overloads). The structure is then designed for the critical load in the same fashion as in the Present System.

The material trade-offs in this example will be based on the weight of the material required to obtain a design with the structural reliability specified. The Type 304 steel tubing will be used as the base line. From Reference 28, Table 2.8.1.1, the reported ultimate tensile strength for Type 304 steel is 75000 pounds per square inch and the density is 0.286 pounds per cubic inch. The strength to weight ratio is:

$$\begin{aligned}\text{Strength to Weight Ratio} &= \text{Strength} \div \text{Weight}\\ &= \frac{75000 \text{ lb}}{\text{in}^2} \times \frac{\text{in}^3}{.286 \text{ lb}}\\ &= 2.62 \times 10^5 \ \frac{\text{lb-in}}{\text{lb}}\end{aligned}$$

For the second material, beryllium, the strength scatter coefficient is approximated from the typical histogram representing test results of the failing load for beryllium tubing as shown in Figure 19 as follows:

$$\begin{aligned}\gamma_S &= \frac{\text{HI-LO}}{2(\text{HI+LO})}\\ &= \frac{155-85}{2(155+85)}\\ &= .146\end{aligned}$$

where HI is the largest observed strength and LO is the smallest observed strength in the test results. When this strength scatter and the *standard reliability goal are used, the LTFS (from Figure* 6) is 2.85 and the OTFS (from Figure 7) is 1.09.

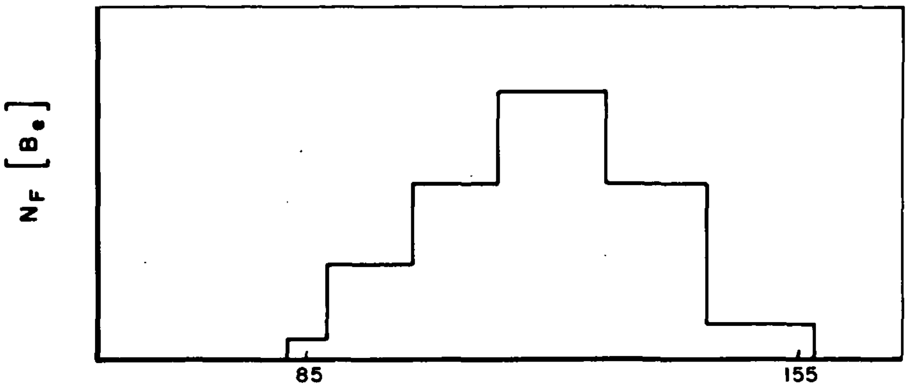


Figure 19. Typical Histogram of Number of Failing Articles versus Failing Load for Beryllium

Once again, the Design Loads for Limit and Omega Conditions are computed. The Limit and Omega Loads remain at $1 \times 10^6$ pounds and $1.2 \times 10^6$ pounds, respectively, but the LTFS and OTFS have increased, making the Design Loads $2.85 \times 10^6$ pounds for Limit and $1.31 \times 10^6$ pounds for Omega. Since the Limit Design Load is critical for this material, the structure is designed to sustain $2.85 \times 10^6$ pounds. (Note that the Design Load for the Limit Condition for beryllium structure is different from the Design Load for the Limit Condition for the steel structure). The strength-to-weight ratio for beryllium is $5.97 \times 10^5$ pounds-force inches per pound-mass as computed from the data in Table 9.2.1.1 of Reference 28.

The required weight of steel and beryllium structure can be computed by dividing the Design Load by the strength-to-weight ratio; i.e.,

Required Weight = Design Load ÷ Strength/Weight

The required weight of the steel tubing is:

$$= 1.41 \times 10^6 \text{ lbs} \div 2.62 \times 10^5 \frac{\text{lb-in}}{\text{lb}}$$
$$= \frac{5.39 \text{ lb}}{\text{in}}$$

and for the beryllium:

$$= 2.85 \times 10^6 \text{ lbs} \div 5.97 \times 10^5 \frac{\text{lb-in}}{\text{lb}}$$
$$= 4.78 \frac{\text{lb}}{\text{in}}$$

Taking the beryllium-to-steel ratio, the relative weight of beryllium to steel for the thrust structure becomes:

$$\frac{4.78 \ \frac{lb}{in^3}}{5.39 \ \frac{lb}{in^3}} = .887 \text{ or } \frac{1}{1.125}$$

Thus, .887 pounds of beryllium could be used with the same reliability as 1 pound of steel. This ratio is less favorable to beryllium than obtained if a uniform factor of safety were used for both materials as in the Present System. However, because of the higher strength scatter associated with beryllium, the gain in weight saved in the structure is traded for a consistent level of reliability.

For the Lockalloy tubing, the same comparison can be made. Starting with a histogram similar to Figure 19, a strength scatter can be derived (no data available). For the sake of this example, the strength scatter is assumed to equal 0.07. Referring again to Figures 6 and 7 with this value for the strength scatter and the standard structural reliability goal, the values of LTFS and OTFS are 1.51 and 1.0, respectively. The design load for Limit and Omega Conditions are, therefore, $1.51 \times 10^6$ pounds and $1.2 \times 10^6$ pounds, equalling the product of the Limit and Omega Loads and the TFS, respectively.

Assuming the strength to weight ratio to be $3.54 \times 10^5$ pound-force inch per pound-mass, the required weight of Lockalloy is:

$$\frac{1.5. \times 10^6 \ lb}{3.54 \times 10^5 \ \frac{lb\text{-}in}{lb}} = 4.26 \ \frac{lb}{in}$$

and the relative weight of Lockalloy to steel is:

$$\frac{4.26}{5.39} \ \frac{lb/in}{lb/in} = .790$$

Thus, .790 pounds of Lockalloy will produce the same reliability as 1 pound of steel.

The strength-to-weight ratio of Lockalloy is lower than that of beryllium; but the more consistent failing strength, as reflected by the lower strength scatter, permits a lower LTFS and a lighter weight, more efficient structure. The inconsistency in strength of the more brittle material, beryllium, as reflected in the higher strength scatter, requires larger factors of safety to provide the needed structural reliability.

In conclusion, the minimum weight structure can be made with the Lockalloy material, even though the Design Load is higher than that for steel. Although this example is greatly simplified, it illustrates the trade-off technique that can be employed in the design process.

## 4.4 Example of Thermal Considerations in Designing with the QSDC Procedure

In order to demonstrate an application of the QSDC Procedure (References 1 and 5) to a problem involving elevated temperature environment for a structure, the following hypothetical problem is presented. Consider the design of a beam element of the support structure of the ablative heat shield of an Apollo-type entry vehicle. The beam must be designed to carry a uniformly distributed pressure of w pounds per inch as shown in Figure 20.

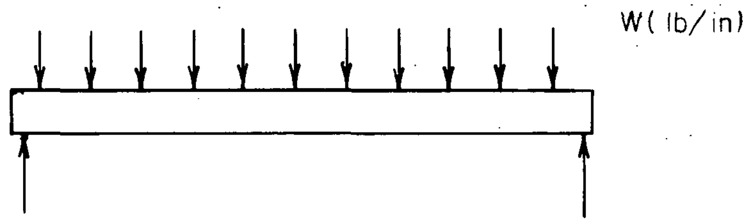


Figure 20. Typical Beam Loading for Heat Shield Support

During the entry the ablative shield can be expected to conduct a certain amount of heat energy into the beam, resulting in a temperature rise and a strength degradation of the structure.

The following assumptions are made:

1) No thermal stresses exist in the beam.
2) There is no inelastic material behavior during the entry.
3) The entire effect of temperature is a reduction of the material strength.
4) The load and temperature experienced by the structure are specified by the trajectory of the entry.
5) The entry trajectory is fully specified by the entry velocity, V.

Utilizing these assumptions the QSDC procedure can be applied in four steps: (L) establish Limit and Omega Conditions (defined) in Section 2.2.2); (2) establish Limit and Omega Loads (Section 2.2.3); (3) obtain design Limit and Omega Loads (Section 2.2.4); and (4) design for the most critical design load to obtain a zero margin of safety at that load (Section 2.2.5).

The QSDC Procedure requires that two separate and distinct conditions be established for any operation. These conditions are the Limit Condition, that condition which can be expected to occur during normal operation of the vehicle, and the Omega Condition, which is not expected to occur during normal operation but is considered to be possible. Generally, exceedance of the Limit Condition should be an infrequent occurrence, say a probability of exceedance of $10^{-2}$. Exceedance of the Omega Condition should be very rare, say a probability of exceedance of $10^{-4}$. These conditions are then said to specify the particular operation.

In the hypothetical problem, the organization responsible for controlling the entry velocity would be required to utilize past statistics, rational analysis, experience, judgement, and any other means to establish the Limit and Omega entry trajectories by defining the Limit and Omega Conditions for entry velocity. If there were insufficient past statistical data on this problem, the responsible organization might conclude that on the basis of rational analysis and judgement, an entry of 37000 feet per second is the maximum velocity required for normal operations and mission success and that an entry velocity of 41000 feet per second is the worst-possible velocity that could result. These then become the Limit and Omega Conditions, respectively, and are binding requirements on the group responsible for the entry velocity.

A graphical representation of this state of affairs is given in Figure 21.

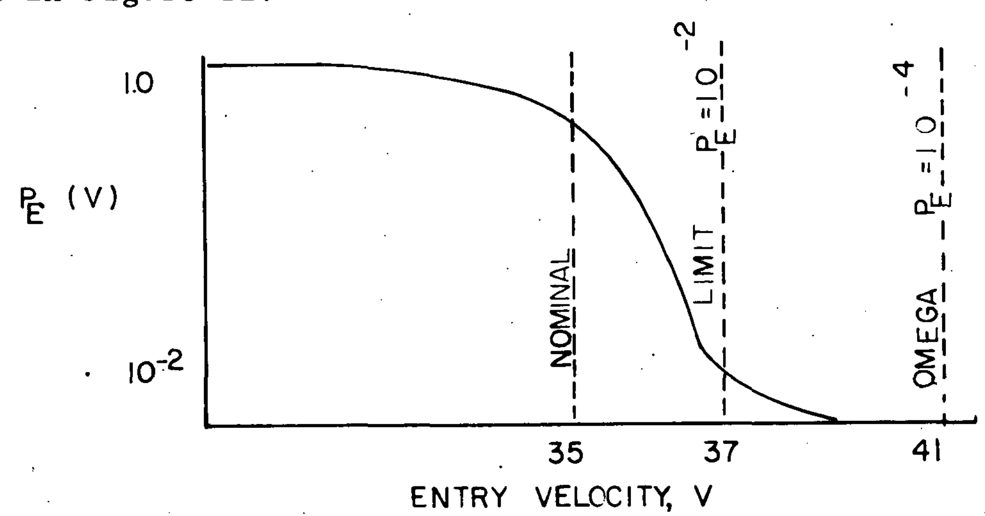


Figure 21. Typical Probability of Exceedance of Entry Velocity

Once the Limit and Omega Conditions have been established, the following are true:

(1) Any condition below Limit must not result in a structural failure.
(2) Any condition greater than Limit but less than Omega must be survivable by "most" structures.

The loads that the structure encounters during each discrete condition must now be obtained for the structural designer.

The QSDC Procedure specifies two levels of external loading that must be considered during the design. The Limit Load is defined as the most critical load associated with the conditions within the Limit Condition envelope, and the Omega Load is the most critical load associated with the conditions within the Omega envelope. In many cases the Limit and Omega Loads are found to correspond directly to the Limit and Omega Conditions, thus eliminating the need to consider other conditions. For the example problem, assume this correspondence holds:

| | |
|---|---|
| LIMIT CONDITION: | V = 37000 fps |
| LIMIT LOADS: | W = 100 lbs/in<br>T = 500°F |
| OMEGA CONDITION: | V = 41000 fps |
| OMEGA LOADS | W = 123 lbs/in<br>T = 800°F |

Note that there is no factorial relationship between the Limit and Omega Loads. These loads arise from two separate requirements and as such are dependent only on the transfer function between the Limit and the Omega Condition and the local loads on the component under consideration.

It now becomes the structural designer's problem to design the structure so that (1) "no" failure can be expected at the Limit Condition and (2) most vehicles can be expected to survive to the Omega Condition. To accomplish these goals, the QSDC Procedure defines Design Limit and Omega Loads that are loads for the Limit and Omega Conditions obtained by multiplying the Limit and Omega Loads by appropriate factors of safety. These factors, known as the Limit TFS and the Omega TFS, are shown on Figures 6 and 7. They were derived in Reference 1 to account for the observed scatter in strength, the meaning attached to the term "most" used above (i.e., the structural reliability goal), and the number of independent tests that the resulting structure must pass for design qualification. The design loads are determined as follows:

DESIGN LOAD FOR THE LIMIT CONDITION = LIMIT LOAD X LIMIT TFS

DESIGN LOAD FOR THE OMEGA CONDITION = OMEGA LOAD X OMEGA TFS

For the example problem, suppose that the structure will have one test, the structural reliability goal is standard, and the strength-temperature envelope is given in Figure 22. The statistical scatter in the strength can be approximated from the envelope using the procedure of Section 3.3.1 as:

$(\gamma_s)_{70} = 0.051 \qquad (\gamma_s)_{500} = 0.058 \qquad (\gamma_s)_{800} = 0.063$

Utilizing the TFS curves of Figures 6 and 7 and the allowable ultimate stress given in Figure 22, the following can be shown:

$(\gamma_s)_{500}$ = 0.058; therefore, LIMIT TFS = 1.39

$(F_{T_u})_{500}$ = 54 KSI

$(\gamma_s)_{800}$ = 0.063; therefore, OMEGA TFS = 1.00

$(F_{T_u})_{800}$ = 35 KSI

Consequently, the design loads are as follows:

DESIGN LOAD FOR LIMIT: W = 100 x 1.39 = 139 lbs/in
T = 500° F

DESIGN LOAD FOR OMEGA: W = 123 x 1.00 = 123 lbs/in
T = 800° F

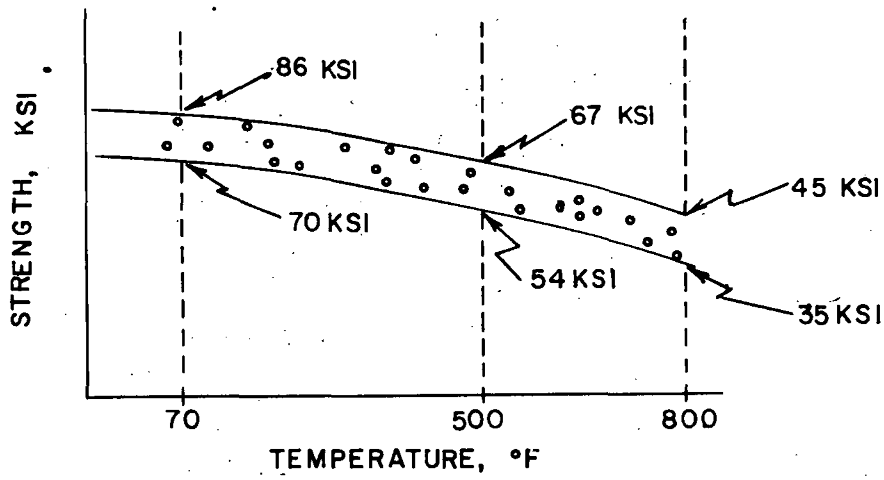


Figure 22. Typical Strength vs. Temperature Curve for the Heat Shield Support Material

The designer must now provide a zero margin of safety for the most critical of the two design load cases given above. If $F_T$ is the maximum stress for a rectangular cross section of fixed depth, the designer requires that

$$\frac{F_T}{F_{T_u}} = \frac{C\ W}{AF_{T_u}} \leq 1.0$$

where C is a constant and A is the cross-sectional area of the beam. Then for

DESIGN LIMIT LOADS: $A = \frac{C\ W}{(F_{T_u})_{500}} \geq 0.262\ 10^{-2}C$

DESIGN OMEGA LOADS: $A = \frac{C\ W}{(F_{T_u})_{800}} \geq 0.352\ 10^{-2}C$

Thus, the Omega Condition is the critical condition, requiring the larger beam cross section.

If the conventional 1.5 factor of safety were applied to the Limit Loads, the required area would be $0.283 \times 10^{-2}C$. Since this is 20 percent less than that required for the Omega Condition, failure would occur at a velocity between Limit and Omega. The probability of exceedance of this failure condition (with 1.5 F.S.) would be greater than the $10^{-4}$ value for the Omega Condition. Thus, the conventional 1.5 factor of safety would not provide the desired standard structural reliability.

The general problem associated with a space shuttle entry, although much more complicated, is basically the same as the illustrated problem. For instance, NASA SP-8057 (Reference 2) currently indicates that the entry trajectories of the shuttle can be restricted to a nominal trajectory corridor and that the design may be based on this nominal corridor plus some dispersion. In the QSDC terminology this design corridor then becomes the Limit corridor. Similarly, an Omega corridor, reflecting the very rare excursion out of the Limit corridor, can be defined. Figure 23 indicates the relationships that might exist. Then, for any particular part of the structure, the requirements of (1) "no" failure within the Limit corridor and (2) "most" survive within the Omega corridor must be met.

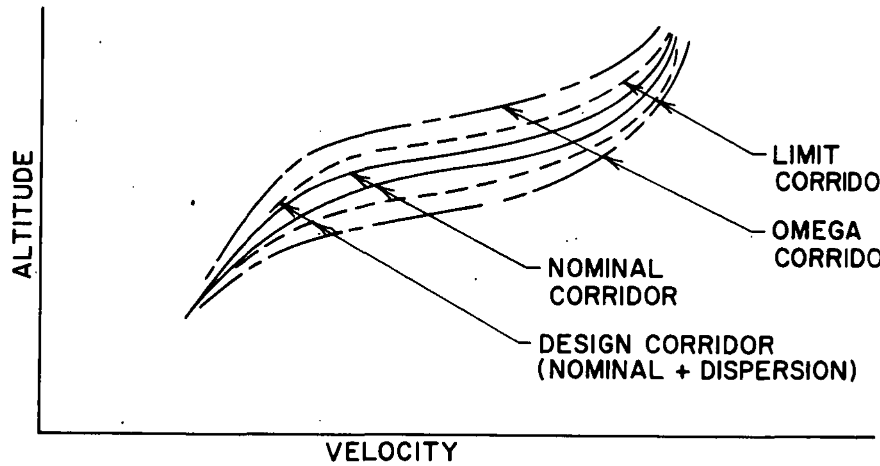


Figure 23. Typical Entry Trajectories

Of course, many of the limiting assumptions on the structural behavior at elevated temperatures will need to be relaxed since creep can occur, thermal stress may be present, permanent degradation of material strength will be present, temperature distributions may not be uniform, and so on. However, to account for the temporary loss in strength due to elevated temperature, the QSDC Procedure can be applied as it stands. Consideration of more complex problems will require some modification of the procedure, but the basic philosophy should carry through.

## 4.5 Illustration of Design Condition Definition for Combined Conditions

The QSDC Procedure handles the problem of combined loads in much the same manner as the Present System. However, as in the single load case, a specific overload requirement is established. The Present System defines the Limit strength requirement for combined loads as the ability to sustain all the Limit Loads simultaneously. The QSDC Procedure defines the Limit strength requirement in the same manner but with one variation: The Limit strength requirement for combined loads is defined as the ability to simultaneously sustain all the Limit Loads which are the result of the combined operational conditions experienced.

For example, consider the combination of two loads: the first being the compressive load produced in the "stack" by the action of the thrust, inertia forces, and aerodynamic drag. A typical Limit axial load distribution for a shuttle-type booster might be illustated by Figure 24 where the negative values shown are compression. The second load considered will be the tension and compression loads produced by the response of the structure to a gust encounter. Assume that the gust occurs during the ascent phase and normal to the flight path and that the loads are the result of an induced bending moment. The Limit bending moment as a function of the body station of the booster is shown in Figure 25.

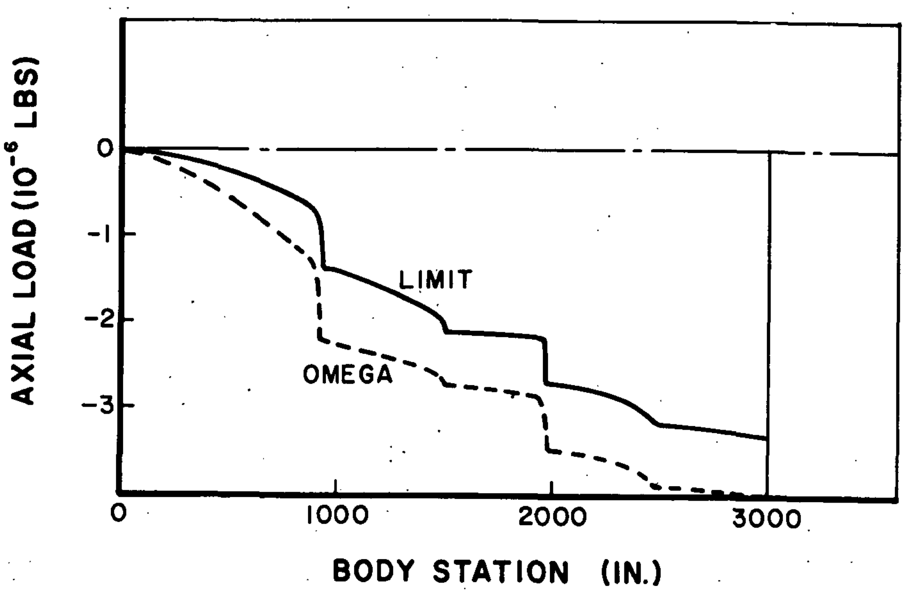


Figure 24. Typical Limit and Omega Axial Load Distribution

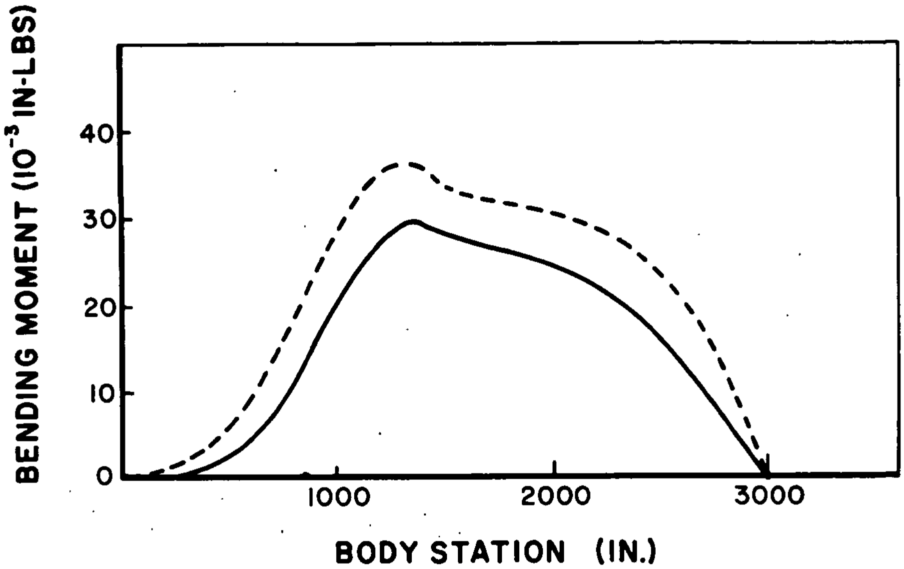


Figure 25. Typical Limit and Omega Bending Moment Distribution for Gust Encounter

For our example, the body station at 1500 inches (hypothetically, an intertank section) has been determined as the critical station for the above combined loads. From Figure 24 the axial load equals $2.1 \times 10^5$ pounds compression, and the bending moment from Figure 25 is 28,000 inch-pounds. The two loads may be combined to produce the Limit Load for the combination of thrust and gust encounter. The Limit Load for the combined loading is shown as the combined Limit spanwise load distribution in Figure 26.

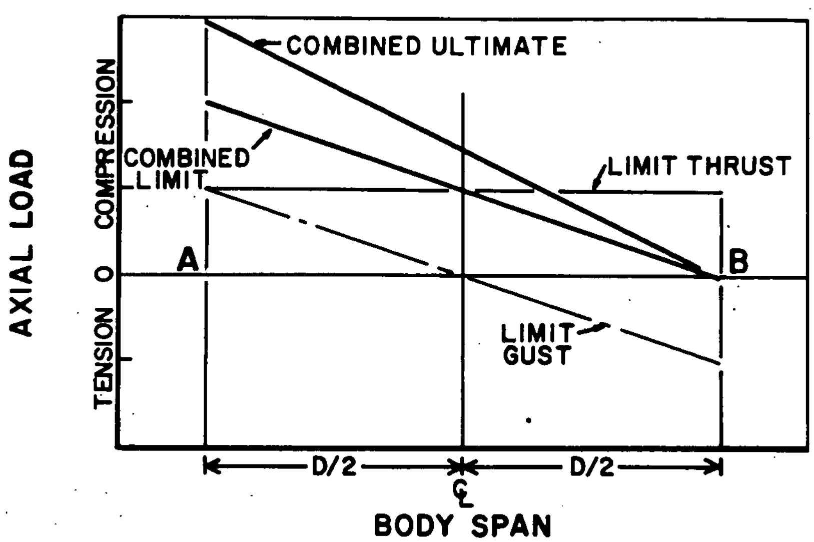


Figure 26. Typical Spanwise Load Distribution at Body Station 1500 for Combined Loads (Present System)

Note that a zero load requirement exists at point B on the structure. If the present system were employed here to define the overload requirement for tension, the structure would have no overload capability. (The Present System assumes that the 1.5 FS accounts for the overload condition.) By multiplying the zero tension requirement by 1.5, the Ultimate Load would still be zero in tension; hence, there is no increase in capability and, therefore, no overload capability.

It is recognized that designing for the Limit Load by itself is not sufficient. The Present System employs a 1.5 FS to insure that the strength will be sufficient for the Limit Loads and to provide for a sufficient overload capability. Similarly, the QSDC Procedure employs a factor of safety (the LTFS) to insure that the strength will be sufficient for the Limit Loads, but the overload capability is defined by a separate requirement, that is, the Omega Condition and its factor of safety, the OTFS. This method ensures that the overload capability is designed into the structure, whereas the Present System can only imply a true overload capability. The following example will illustrate what is meant.

Considering the combined Limit Load distribution of Figure 26, the Present System would define the combined Ultimate Load distribution by multiplying the combined Limit Load distribution by the 1.5 factor of safety as shown in the figure. Note that the maximum compressive load (at point A) has a discrete overload capability (the difference in load from the Limit curve to the Ultimate curve) and that the minimum compressive load (at point B) has no overload capability. That is, the zero compressive load factored by 1.5 is still a zero compressive load; hence, there is no difference in load and no overload capability. Obviously, since the vehicle is symmetrical, the maximum compressive load would provide more than enough overload capability for the minimum compressive load. However, if the minimum compressive load were to become a tensile load, there is no coverage of this strength requirement by the maximum compression load. A tensile load at point B can result from either a higher bending moment than expected or a lower thrust loading with the same bending moment. The Present System, however, cannot consider these overload possibilities by simply factoring the Limit Loads by the factor of safety to obtain an "overload" capability.

The QSDC Procedure, however, does consider the overload conditions separately and discretely from the Limit Conditions. (Therefore, the true overload condition is considered.) The load distribution for the Omega level of thrust and of the condition of gusts encountered are shown in Figures 24 and 25. A discussion of how the Omega level of combined conditions is determined can be found in Section 2.2.2. The spanwise load distribution at the Omega level of each condition would appear as in Figure 27. The QSDC Procedure defines the combined Omega Load distribution as follows: The combined Omega Load distribution for two loads is defined by two separate distributions where the Omega Load distribution of one condition is combined with the Limit Load distribution of the other. In our example, the combined Omega Load distribution for the conditions of thrust and gust encountered by a hypothetical vehicle at station 1500 would be as follows: The spanwise Omega Load distribution due to the thrust (from Figure 27) is combined with the spanwise Limit Load distribution due to the gust (from Figure 26) for the first of the combined Omega Load distributions (Omega 1, Figure 27). The second combined Omega Load distribution (Omega 2) is defined as the sum of the spanwise Omega Load distribution due to the gust (Figure 26) and the spanwise Limit Load distribution due to the thrust (Figure 27). By taking the larger value of load from either of the Omega Load distributions, the combined Omega Load distribution can be defined. The result of combining the two Omega distributions is a less severe compressive load than that of the Present System design (compare point A of the Omega 1 distribution with the combined Ultimate distribution) and a small tension requirement where the Present System has none (point B).

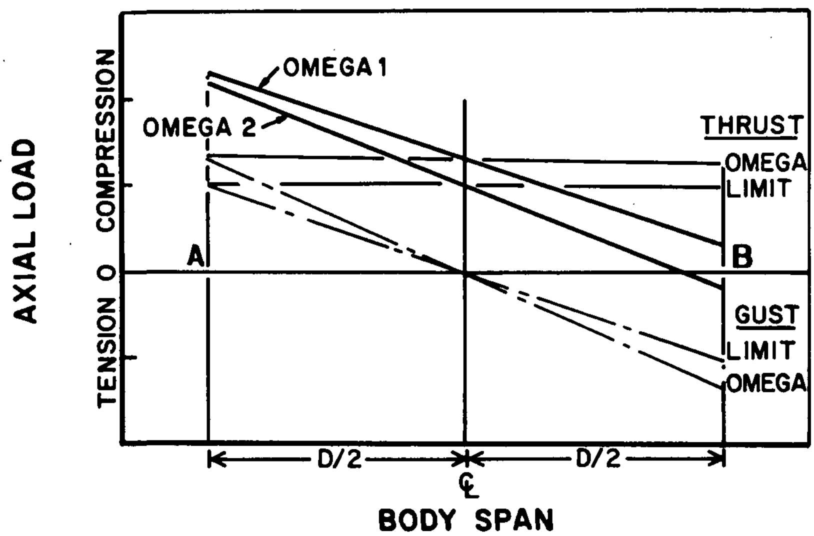


Figure 27. Typical Spanwise Load Distribution at Body Station 1500 for Combined Loads (QSDC Procedure)

Thus, for the combined load situation, the QSDC Procedure creates understrength and overload strength requirements as in the single load situation. However, these strength requirements are interpreted as two distinct load distributions that must be sustained by the structure. The load distributions are the combined Limit Load distribution and the combined Omega Load distribution.

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APPENDIX A

SUMMARY OF QSDC PROCEDURE FOR SPACE SHUTTLE APPLICATIONS

LIST OF ILLUSTRATIONS

## 1. INTRODUCTION

The purpose of this study (NAS8-26918) is to provide recommendations for improved structural design criteria applicable to the Space Shuttle. To approach the problem logically, it is necessary to establish the objectives of the structural criteria. It is generally accepted that the major objective is to define operational conditions that the vehicle is required to survive without structural failure. An adjunct to this objective is the specification of a proof of compliance procedure. This procedure must be acceptable for demonstrating that the structural system will survive the defined operational conditions. It is interesting to note that in NASA SP-8057 (Reference 1*) there is no quantitative definition of an objective. Neither is there one in MIL-A-8860 (Reference 2).

Reference 3 developed the philosophy of a probabilistically based, deterministic system for defining structural design criteria. The concept is propounded that the structural system is expected to have both the capability of surviving overload situations and a reserve against understrength situations. Requirements for providing these two capabilities are identified separately and explicitly. These requirements are based on probabilistic considerations, but the resulting design conditions are established as deterministic requirements. This is the key to making the new procedure practical and administrable.

This report is intended to summarize Reference 3 and together with Reference 4 describe the application of the Reference 3 concept to the Space Shuttle. To facilitate the understanding and acceptance of the Reference 3 concept, this report presents the basics of the concept in the briefest possible form for quick assimilation. Reference 4 expands the concept and discusses the rationale in more detail. Reference 5 presents engineering data and specific procedures for application of the concept to the structural design of the Space Shuttle and other aerospace vehicles.

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* All references in Appendix A relate to listing on page A-20.

## 2. GENERAL

This report describes the concepts that define structural design criteria as developed in Reference 3. For simplicity and to differentiate from the Present System (typified by the 1.5 Factor of Safety), this new procedure is designated as the QSDC Procedure (standing for Quantitative Structural Design Criteria by Probabilistic Methods). Although the QSDC Procedure was developed for aircraft applications, it is universal and will be described in this summary in a context appropriate to the Space Shuttle.

The methodology of the QSDC Procedure is presented in this summary in terms of the intent of the various steps. The implementation of these intentions is described in detail in References 4 and 5.

All structural failures can be divided into two types: understrength or overload (see Figure 1). The line of demarcation between the two is somewhat arbitrary. It depends on a decision defining those environmental conditions which will be imposed on the structural system by the nonstructural systems and which the structural system is expected to survive. In the QSDC Procedure the line of demarcation becomes a zone bounded by two discrete operational* conditions designated as the Limit Condition and the Omega Condition. As shown on Figure 2, these two conditions separate the entire range of severity of a particular operational condition such as the longitudinal load factor into three regions:

1. The Safe Region
2. The Overload Region
3. The Gross Overload Region

The Limit Condition is defined as the upper boundary of normal and expected operations. This definition is considered to be satisfied in the QSDC Procedure if the Limit Condition is exceeded only once in one hundred vehicle lifetimes.** In the initial design of a new vehicle such as the Space Shuttle, the decision on the magnitude of the Limit Condition is made on the basis of a probabilistic prediction of the lifetime operational spectra. If

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* Hereafter, the environmental conditions which may be imposed on the structural system by pilot actions, ground handling, hydraulic and pneumatic subsystems, aerodynamic heating and malfunctions will be called operational conditions for simplicity.

** This is for what is designated a Standard Vehicle in Reference 3. Higher or lower values may be used for different missions but the principle remains unchanged.

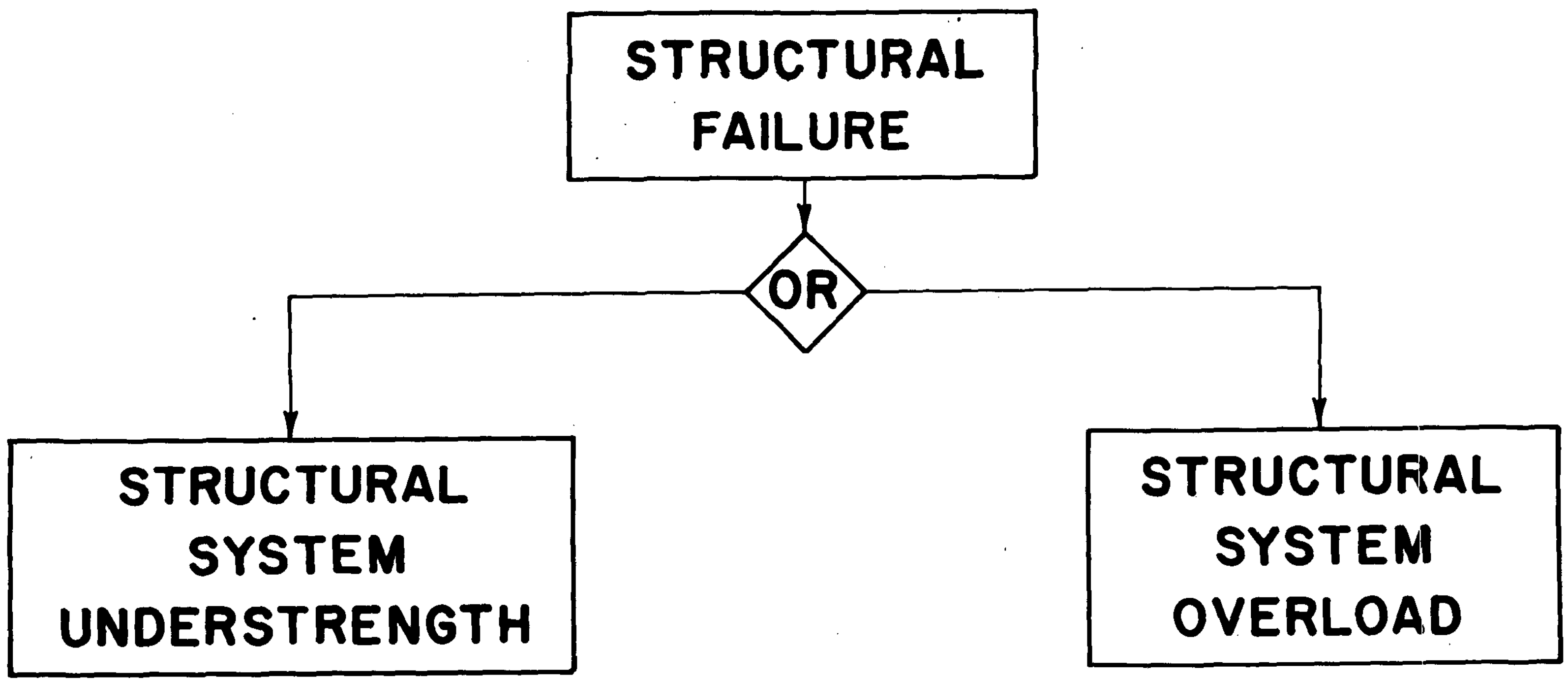


Figure 1. Basic Fault Tree of Structural Failure Modes

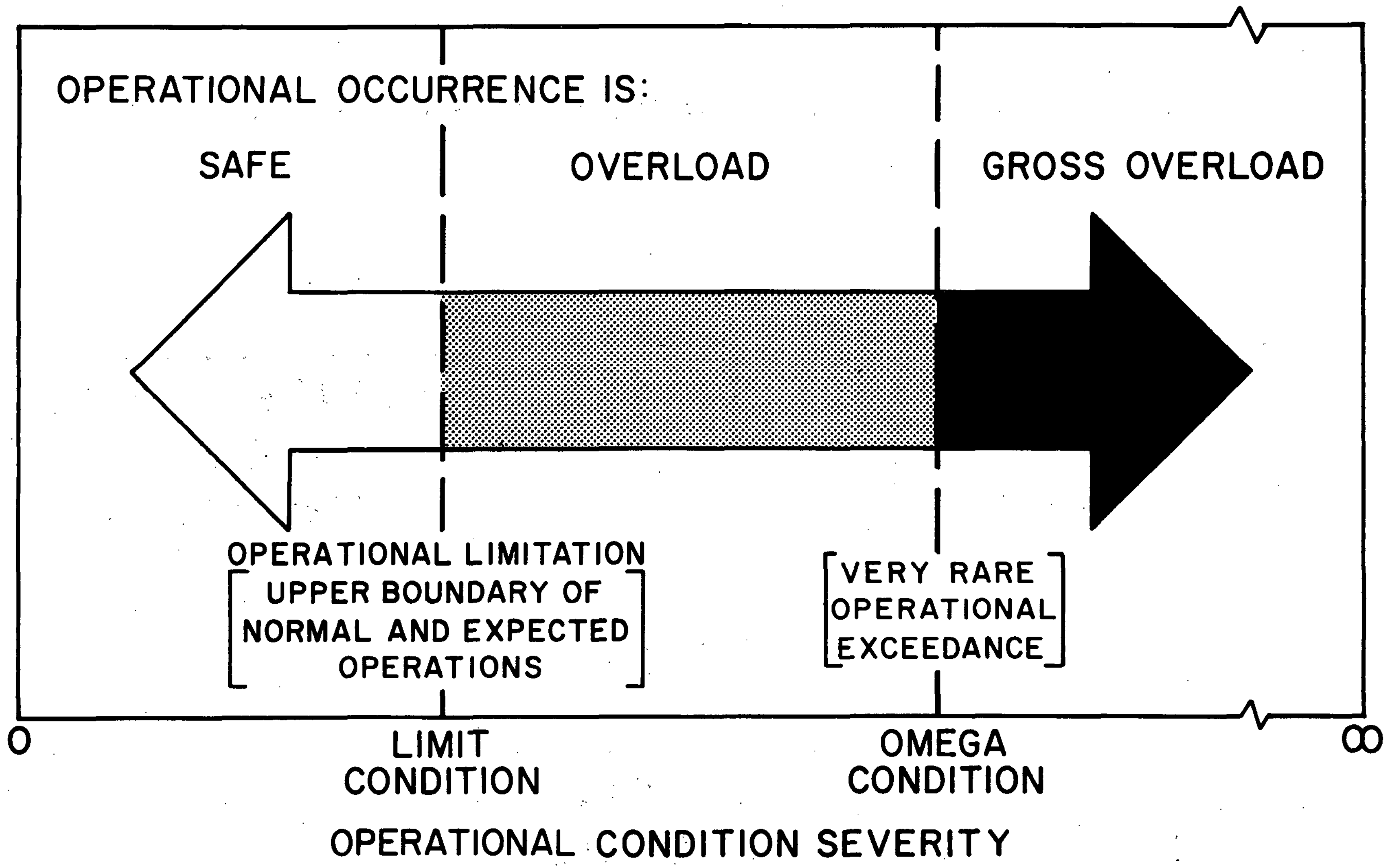


Figure 2. Relationship of Limit/Omega Conditions to Operational Regions

insufficient statistical data are available for a rational calculation of the Limit Condition, the decision is made on a judgment basis with the intent of satisfying the basic definition of a Limit Condition as the upper boundary of normal and expected operations.

Once the decision is made, the defined Limit Condition (initially chosen on a probabilistic basis) is deterministic and is no longer dependent on the method by which the decision was made. The choice is made somewhat self-fulfilling by establishing an Operational Limitation which coincides with the Limit Condition. Since the Limit Condition by definition is "expected," it and all lesser conditions are not overloads. Since operations which exceed the Operational Limitation are prohibited, any such exceedance is by definition an overload. These definitions are noted in Figure 2. The definitions of the Limit Condition and the Operational Limitation are, for all practical purposes, the same as in the Present System.

The QSDC Procedure defines a second level of operational condition severity that has been designated as the Omega Condition. This operational condition should be one that will be exceeded very rarely, if ever. In the QSDC Procedure the Omega Condition should be chosen so that the probability of exceedance is less than the complement of the Structural Reliability Goal. For the Standard Vehicle previously described, the Structural Reliability Goal is 0.9999, so the probability of exceedance of the Omega Condition should be less than 0.0001. The same statistical data used for defining the Limit Condition should be used for making the prediction on which the Omega Condition decision is made. Again, if insufficient statistical data are available for a rational prediction of the Omega Condition, the decision is made on a judgment basis. The choice should define a very rare operational condition. It should also represent a condition which is obviously a gross overload as noted on Figure 2, i.e., well beyond the range of a minor penetration of the designated Operational Limitation. Finally, the Omega Condition should be one at which structural failure will be tolerated with the implication that the corrective action for such a failure will not be to strengthen the structural system but to change the nonstructural system to prevent future operations at or beyond the Omega Condition.

The defined Limit and Omega Conditions establish an interface between the structural and nonstructural systems. Figure 2 and the previous discussion describe the relationship this interface imposes on the nonstructural system. For the structural system, the Limit Condition represents an operational level below which "no" structural failure will be tolerated since such operations are within the Operational Limitation. "Most" of the vehicles should survive operations to the Omega level without structural failure, but no vehicles are required to survive beyond the Omega Condition. Since the Omega Condition is expected to occur once in 10,000 vehicle lifetimes and less severe conditions more often, "most" of the structural systems must survive this Omega Condition or the failure rate will be greater than 1:10000. In such cases the Structural Reliability Goal of 0.9999 could not be achieved. The relationship imposed by the Limit/Omega interface on the structural system is shown on Figure 3. Any failure in the Gross Overload Region, beyond the Omega Condition is, by definition, not an understrength failure. A failure at the Limit Condition is so far below the intended strength that it is by definition a "gross" understrength, and the corrective action is predetermined to be an increase in the strength of the structural system.

A qualitative description of the characteristics of the three operational regions delimited by the Limit and Omega Conditions is presented on Figure 4. In the Safe Region, below the Limit Condition, all operations are permissible and expected to be "safe" since they are below the Operational Limitation. Since operations in this region are expected to be safe, structural failure is not tolerated at or below the Limit Condition. If a failure does occur, it is by definition the result of a gross understrength in the structural system and the responsibility for the failure resides with the structural system. Operations beyond the Omega Condition in the Gross Overload Region are not to be tolerated because structural failure is "expected" in this region. Consequently, any failure is by definition a gross overload failure and the responsibility of the nonstructural system that produced the Omega Condition.

The Overload Region between the Limit and Omega Conditions is a transitional region. An occasional violation and penetration of the Operational Limitation will be tolerated, although not approved. Because a realistic assessment of the situation must recognize that violations of the Operational Limitations will occur periodically, some structural capability must be provided to survive these occasional penetrations into the region beyond the Limit Condition. This requirement is qualitatively described by stating that most, but not all, of the structures must survive in this Overload Region. It should be noted that any penetration of the Operational Limitation results in an overload, but the magnitude of the overload varies from a minor overload as soon as the Operational Limitation is exceeded to a gross overload if the entire region is traversed and the Omega Condition is attained. In a similar vein, any failure at less than the Omega Condition represents an understrength situation which varies from a minor understrength at the Omega Condition to a gross understrength if failure occurs at the Limit Condition. Thus, there is a gradual shifting of responsibility for a structural failure in the Overload Region from the structural system to the nonstructural system as the level at which the failure occurs increases from the Limit Condition to the Omega Condition.

The requirements for preventing failure in all three regions are satisfied if four requirements which are related to the Limit and Omega Conditions and described below are satisfied. As discussed previously and as shown on Figure 5, the Limit and Omega Conditions should be chosen and operations controlled so that

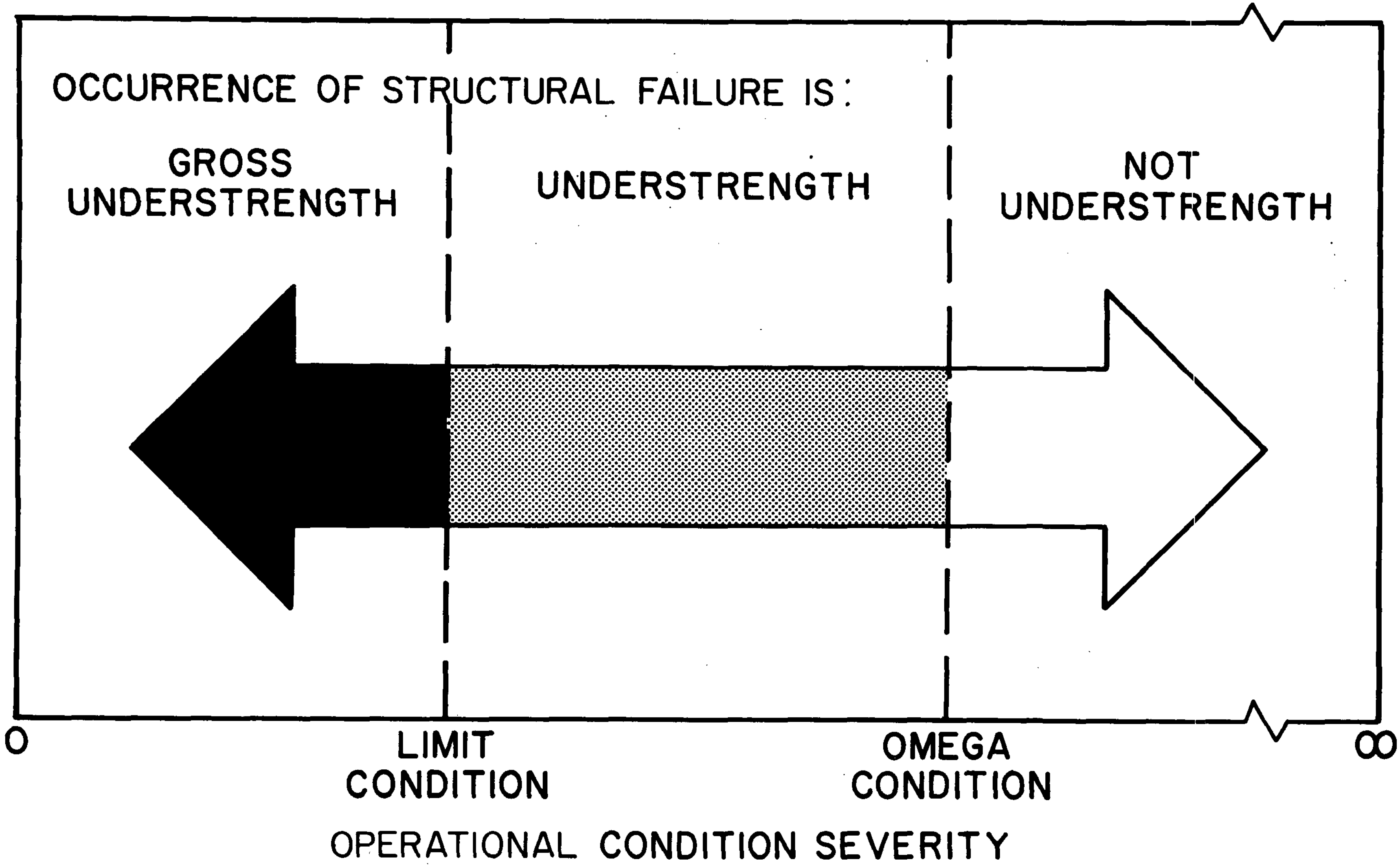


Figure 3. Relationship of Limit/Omega Conditions to Structural Failures

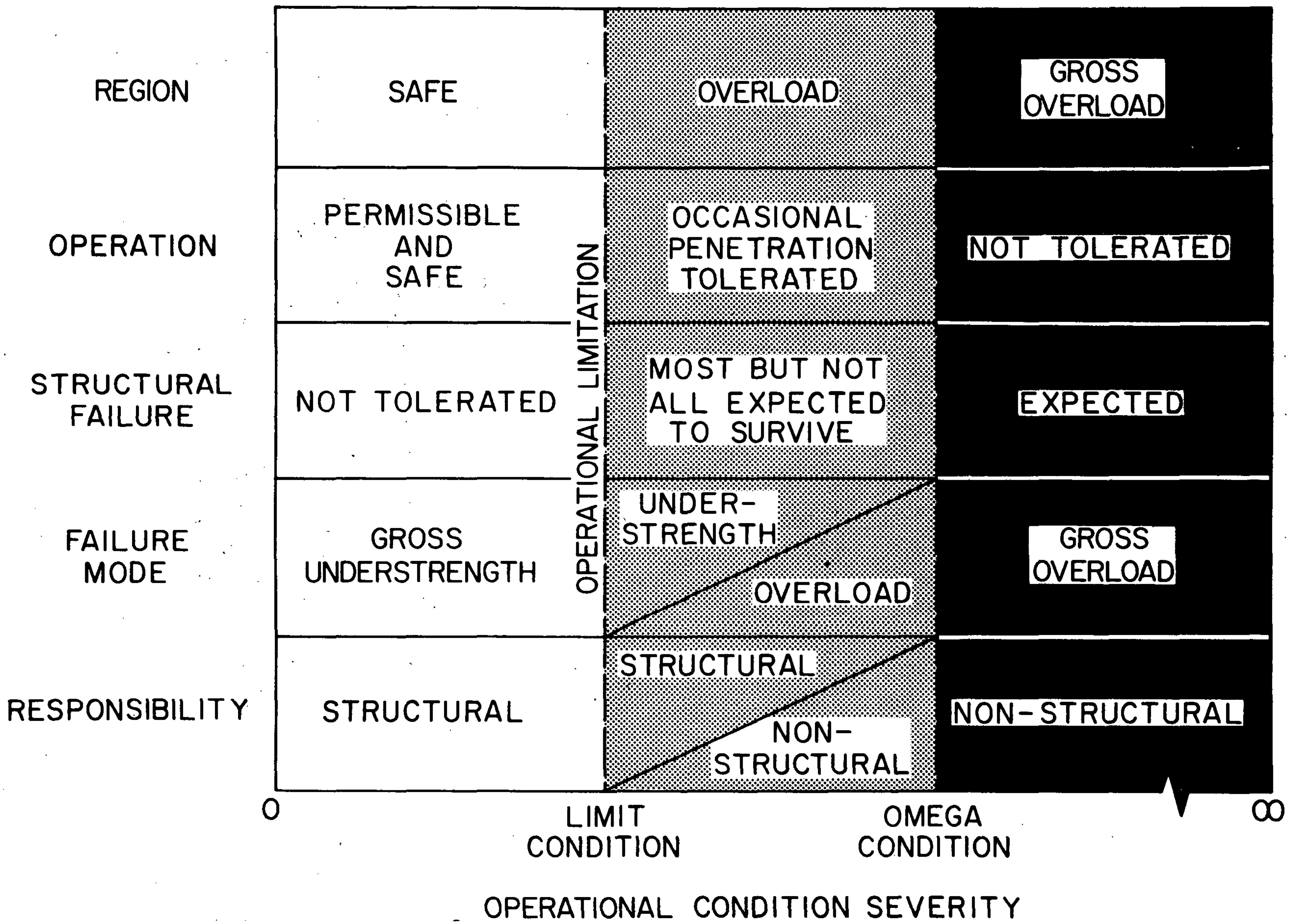


Figure 4. Characteristics of the Three Operational Regions

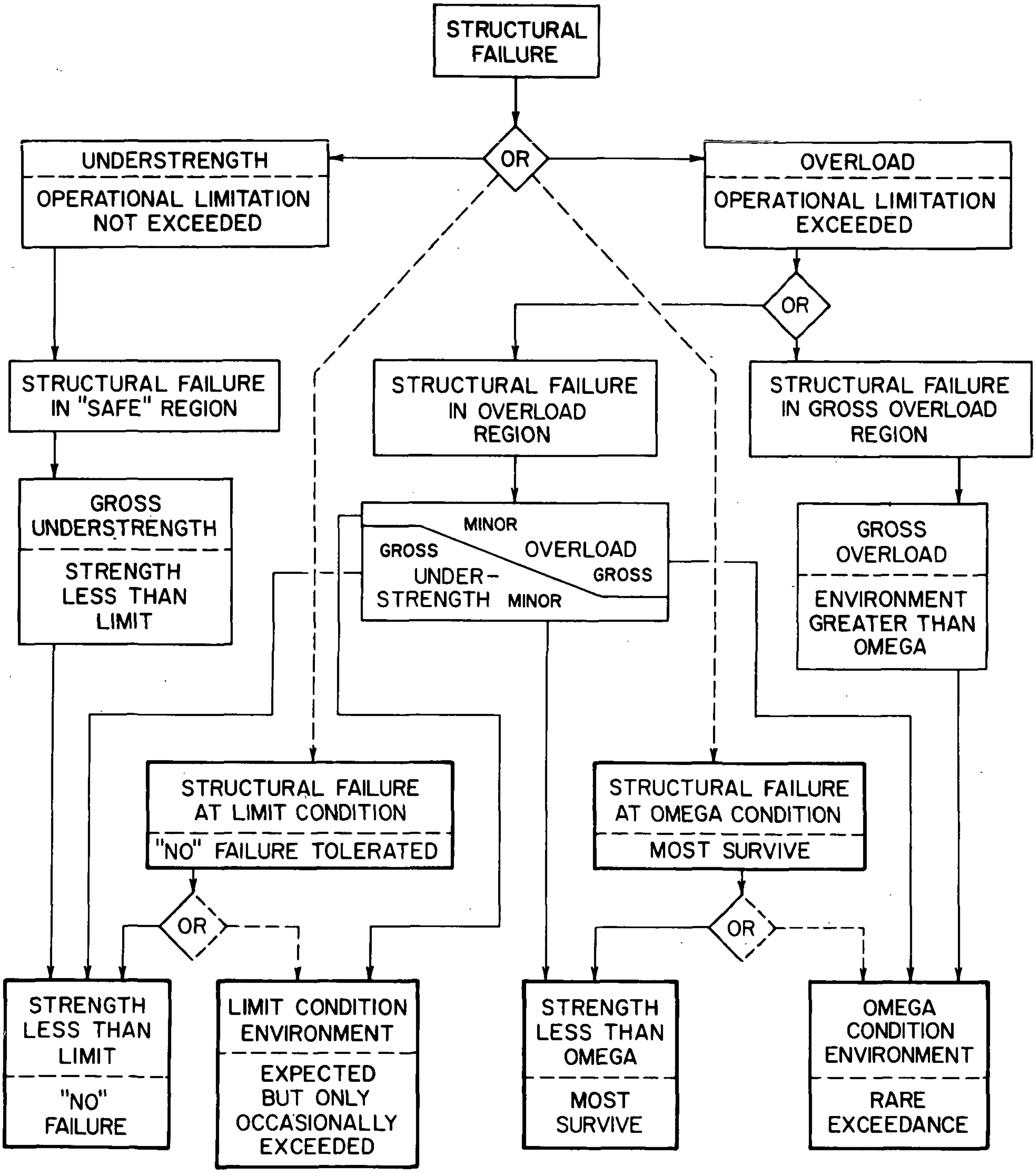


Figure 5. Fault Tree for Structural Failure Prevention

there are few exceedances of the Limit Condition and very rare exceedances of the Omega Condition. The strength of the structural system should range from "no" failure at the Limit Condition to "most" structural systems capable of surviving the Omega Condition. If these four separate requirements are satisfied, the structural failure rate will approximate the frequency of exceedance of the Omega Condition. In addition, most of the failures will be the result of gross overloads and only a small percentage of the failures will be the result of gross understrengths. This latter objective stems from the fact that past experience shows that understrength failures are considered to be less acceptable than overload failures.

A simple Space Shuttle example which illustrates how these qualitative requirements are satisfied is presented on Figure 6. The figure shows the increase in longitudinal load factor with time (due to a decrease in remaining propellant). This load factor could increase to such a high value that a significant weight penalty would be incurred in the design. As a result, present Space Shuttle designs throttle back the engines to restrict the longitudinal load factor to some predetermined value, taken to be 3.0G in this example. To define the Limit and Omega Conditions, an analytical prediction must be made concerning the precision with which the propulsion control system can establish the nominal 3.0G on each launch. As shown on Figure 6, the hypothetical scatter in thrust cutoffs will result in a 3.15G load factor on 1:100 vehicles during their lifetime. A 3.6G load factor is predicted to occur in 1:10000 vehicle lifetimes. These predictions may be made by any rational engineering technique. Judgment may be a major element in the prediction (as it was in this example). However arrived at, the prediction becomes the basis for the decision that the Limit Condition is 3.15G and the Omega Condition is 3.6G. From this point on, the Limit/Omega Conditions are deterministic.

A discussion on how the decision should be validated is presented in Reference 4. However, the basic considerations should be that the propulsion control system and those organizations responsible for it agree that they can hold the longitudinal load factor to 3.15G "most" of the time and 3.6G "all" of the time. They and presumably the Program Manager agree that, if the load factor exceeds 3.15G on any launch, an investigation will be initiated to determine the cause of the overload and the necessary preventative action. Also, the manager of the propulsion control system and the Program Manager agree in advance that, if the load factor ever exceeds 3.6G and structural failure follows, the corrective action will be to modify the propulsion control system rather than to strengthen the structural system.

In short, the decision on the magnitude of the Limit and Omega Conditions should be based on probabilistic considerations whenever possible and on good judgement when no data is available.

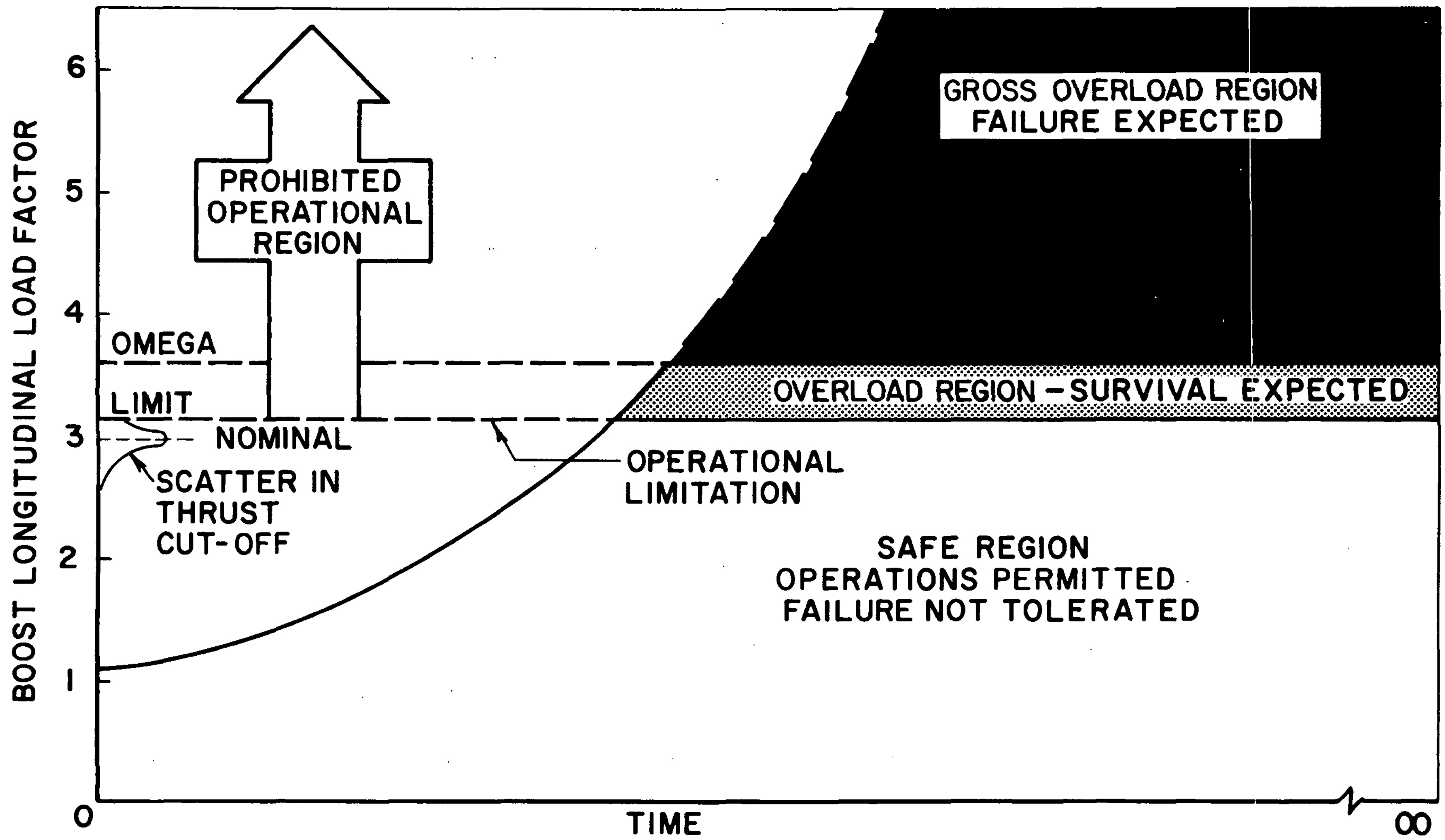


Figure 6. Example--Boost Longitudinal Load Factor by QSDC Procedure

The choice is confirmed and accepted by all concerned. From that time forward any exceedance of the Limit Condition of 3.15G will be recognized as an unacceptable operation which overloads the structural system. Corrective action is promised to prevent any future penetration into the overload region beyond the 3.15G Limit Condition. Finally, it is agreed by all concerned that any operation beyond the 3.6G Omega Condition is expected to result in structural failure so that prevention of such a gross overload is a necessity if structural failure in the Gross Overload Region is to be prevented.

Once it is decided that the Limit Condition for the longitudinal load factor of the Space Shuttle is 3.15G and that the Omega Condition is 3.6G, the structural system in each flight vehicle must satisfy two separate and distinct requirements. The region below 3.15G must be a safe region as shown on Figure 6 with no structural failure tolerated in this region. Note that this requirement is valid regardless of the methodology used to establish the Limit Condition of 3.15G and regardless of whether the defined Limit Condition satisfies the specified requirements. Once the number representing Limit Condition (3.15G) is definitized, that number represents the upper boundary of what must be safe and permissible operations.

The second requirement for the structural system of each Space Shuttle is that most of these structural systems should survive an excursion of boost longitudinal load factor to 3.6G. Note that in meeting this requirement some capability beyond Omega is inevitably provided. However, no commitment is established to provide any specific level of survival beyond Omega, provided that "most" survive Omega. The structure is "expected" to fail in the region beyond Omega. The characteristics expected of the structural system are summarized on Figure 4.

The structural requirements of "no" failure at Limit and "most" survive at Omega are provided by two separate strength requirements. As shown on Figure 7, a reserve to provide against understrength sufficient to cause failure at the Limit Condition is provided by establishing a Design Load for Limit Condition which is higher than the load at the Limit Condition. The magnitude of this reserve will depend on the magnitude of the strength scatter of the particular structure involved, the number of strength tests on separate and independent test structures subjected to the Design Load for the Limit Condition, and the risk level dictated by the vehicle mission. Figure 8 defines a factor called the Limit Design and Test Factor of Safety (LTFS) which is sufficient to achieve the desired result.

The rationale of the LTFS is described in detail in Reference 4. The LTFS is used in the same manner as the 1.5 Factor of Safety in the Present System. However, the LTFS is determined by the increment in the test load necessary to reject all understrength designs which might result in structural failures during operations at or below the Limit Condition. It is a basic premise of

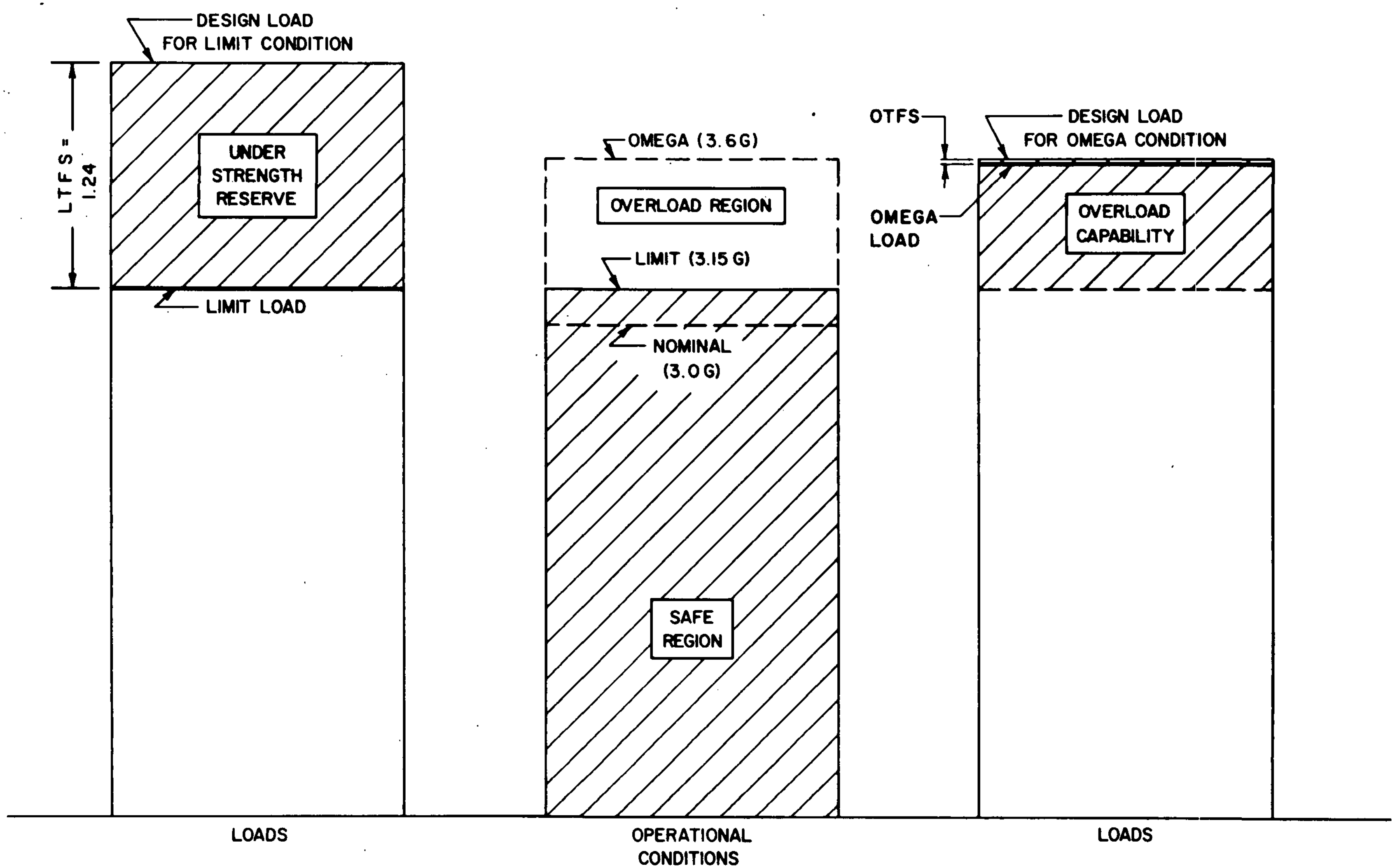


Figure 7. Overload and Understrength Requirements

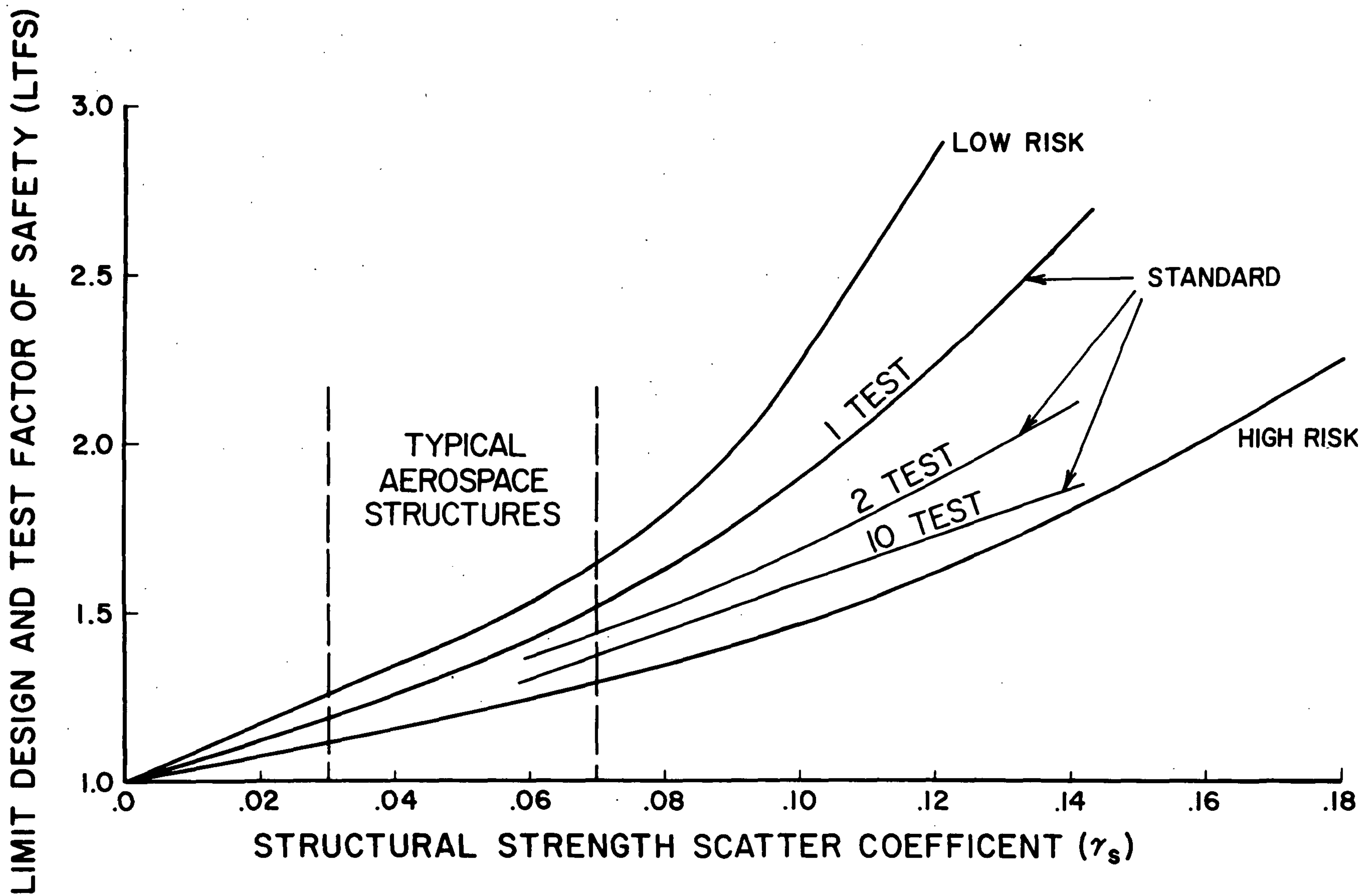


Figure 8. Limit Design and Test Factor of Safety

the QSDC Procedure that understrength designs have occurred in the past and may be expected to occur again in the future when the design strength is predicted by analysis alone.

Strength tests such as static tests of a test article considered to be representative of the flight articles have been considered for many years as a major element in the development of reliable structural systems. The QSDC Procedure continues this reliance on testing but changes the rationalization for the test. Most structural engineers have grown accustomed to thinking that the test "proves" the strength of the design. This assumption is not correct for reasons discussed in References 3 and 4. The test may be used as a contractual or administrative basis for the acceptance of the design, but it does not prove the strength. In the QSDC Procedure the test is used as a means for disclosing errors in the analysis. If the test article fails to support the test loads, the design is rejected. However, some designs that should be rejected pass the test and others that should be accepted fail to pass the test.

The problem is that the strengths of a group of nominally identical structures of a given design are randomly distributed. The test article may be higher or lower in strength than the average strength of the flight articles. As a result, a test article on the low side of the average strength may result in falsely rejecting a "good" design. This possibility is unfortunate because of the cost and schedule delay involved, but the redesign for greater strength will result in changing a design which is already adequate to one which is more reliable than required. Thus, the impact on the reliability performance of the structural system would be beneficial.

But if the test article is on the high side of the average strength, the successful test may result in falsely accepting a "bad" design. This latter phenomenon is sometimes known as "random success." If the strength scatter of the design is small, the range will be quite narrow between flight articles on the low side of the scatter band and a possible random success of the test article on the high side of the scatter band. Thus, a small LTFS will be quite adequate to insure a very low possibility of failure under the load at the Limit Condition after successful test to the higher design and test load defined by the LTFS.

It appears that the strength scatter of most aerospace structures designed in the past in accordance with good practice was small enough so that the usual 1.5 Factor of Safety inherently provided a more than adequate reserve against understrength; consequently, the problem has not been recognized in the past. Certain types of designs that were intuitively recognized as having large scatter (usually vocalized as being inconsistent or erratic in strength) were proscribed in aerospace practice. Brittle materials such as ceramics, extremely high heat treats in steels, and welds in tension were avoided as were very long slender columns. Trends in structural systems indicate that these types of designs are becoming more necessary to meet the demands of advanced systems such as the Space Shuttle. In such cases an LTFS greater than 1.5 may be necessary to maintain the desired structural integrity. On the other hand, the requirement for a low-cost transportation system such as the Space Shuttle demands that the criteria requirements be reduced to a minimum to obtain the lightest possible structural system. The definition of an LTFS in the format of Figure 8 permits the designer to use an LTFS less than 1.5 if he can select materials and configurations with a low strength scatter. When the exigencies of the mission requirements demand structures with a large strength scatter, the larger LTFS required to provide safety in the region below the Limit Condition is called out by Figure 8.

As described above and as shown on Figure 8, the reserve against understrength may be large or small depending on the structural configuration. The requirement for overload capability as shown on Figure 7 is separate and distinct from the requirement for an understrength reserve. There is no factorial relationship between the Design Load for the Omega Condition and that for the Limit Condition. For example, the Limit Load for a vacuum tank designed to operate at sea level would be 14.7 pounds per square inch. Since overpressure could never occur in this situation, the Omega Load would also be 14.7 pounds per square inch. The Design Load for the Omega Condition would be 14.7 pounds per square inch, but the Design Load for the Limit Condition would vary. If the strength scatter were small, the LTFS might be 1.25 in which case the Design Load for the Limit Condition would be 18.38 pounds per square inch. If the strength scatter were large, the LTFS might be 2.1 in which case the Design Load for the Limit Condition would be 30.87 pounds per square inch. In either case, the Design Load for the Limit Condition would be more critical than the Design Load for the Omega Condition. On the other hand, some overload situations may result in an Omega Load which is two or three times larger than the Limit Load. Further complicating the problem of providing overload capability is the variation of temperature and other environmental loads between Limit and Omega Conditions. It is quite possible that the mechanical load at the Omega Condition may be little more than that for the Limit Condition; yet the associated thermal environment may make the Omega Condition much more critical. In any event, the objective for the structural design is to produce a structural system which will survive the Omega Condition in most of the vehicles. Temperature, radiation, corrosion, and other environments which occur simultaneous to the Omega Condition must be considered in determining survival capability.

The final result is a structural system which will possess an adequate but not excessive provision against the four modes of failure shown on Figure 5. This in turn will prevent failures in each of the three operational regions shown on Figure 9, which combines the definitions of Figures 2 and 3 for easy reference.

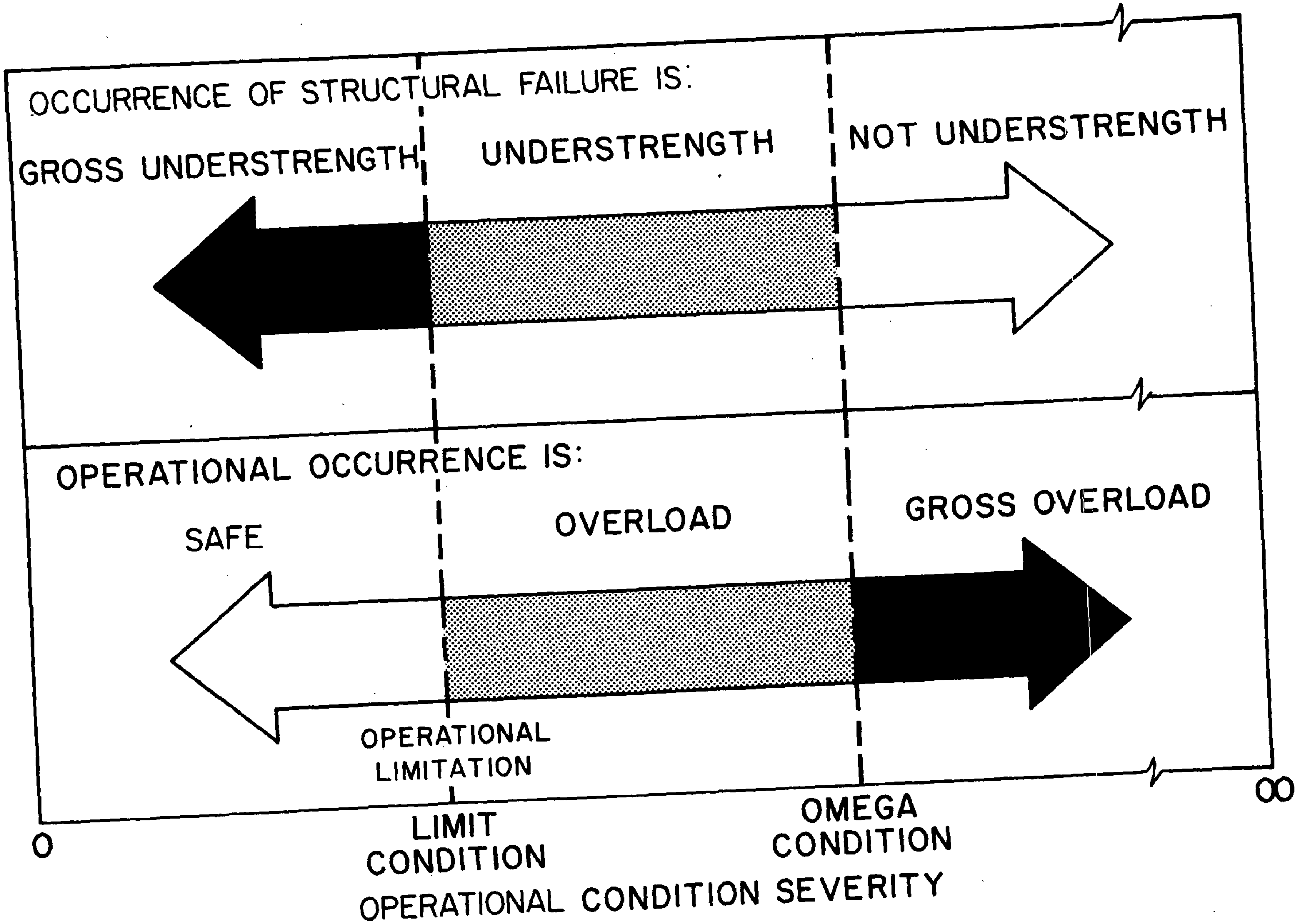


Figure 9. Basic Limit/Omega Relationships

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# APPENDIX B
# ERROR ANALYSIS

## B.1 Introduction

This appendix is included to give the proper perspective to the problems created by design errors in the development of a new piece of hardware such as the Space Shuttle. The design errors considered are load errors and strength errors. The load errors considered are errors in the choice of the design condition and errors in the conversion of operational conditions to external load. The strength errors considered are the analytical errors made in sizing and errors in the material strength, such as heat-treat errors. The impact of these errors on the overall reliability of the structure is discussed.

The QSDC Procedure, as presented in the report proper and summarized in Appendix A, is used here. The manner in which the QSDC Procedure deals with each type of error is also discussed. The justification of the need to consider the possible errors is presented briefly according to the Jablecki/Chenoweth data of Figure B-2 and supplementary data of Figure B-3. These figures are presented as representative of the true state of the art of analysis.

## B.2.1 Loads Errors

Load errors are defined as those arising when the external loads are not consistent with the design conditions or those arising when the design conditions, although interpreted correctly as external loads, are not consistent with the actual mission requirements; that is, either the design condition is right but the conversion to external loads is incorrect or the choice of the design condition is in error. An example of the latter would be the error resulting from ignoring the across-the-fleet variation in the design condition. Suppose that the maximum gimbal angle deflection is specified as 7 degrees. This might be used as a Limit Condition which may become the design condition (if the loads associated with the Limit Condition are the more critical). If the across-the-fleet variation is on the order of one degree, then the choice of the Limit Condition may be in error by as much as 1.0 degree. Thus, the Limit Condition should be specified as 8.0 degrees. If the loading in the component, say diagonal members of the thrust structure, is a linear function of the condition investigated, say gimbal angle, then the design loads for the 7-degree limit will be less than the loads required for the actual limit of 8.0 degrees. In the QSDC Procedure, this type of error is excluded because the choice of the Limit and Omega Conditions is made with consideration of the variability of the condition. The Limit Condition becomes a placard value, that is, it is not to be exceeded. Exceedances, however, do occur even though it is specified by regulation that it is not to be exceeded. When these exceedances occur in the pursuit of the design mission, there is evidence that the

the design condition is too low and hence in error.

The second form of design error is the most common: an error in the conversion of operating conditions to external loads. This error is most commonly an analytical one made in the numerical analysis. For example, suppose that the 8.0-degree gimbal angle Limit Condition is chosen. Hypothetically, the loads analysis shows that on some diagonal member in the thrust structure the load is 50,000 pounds compression at this Limit Condition. The results of operations monitoring might show that the load on the same member is actually 55,725 pounds for the Limit Condition of 8 degrees of gimbal. Thus, it could be said that the interpretation of the Limit Condition as *an external load was in error, although the Limit Condition was* properly chosen.

It should be noted that the loads errors cannot be detected until the vehicle is in operation and the data from the operations monitoring has been observed. The exceedance of the placard Limit in the pursuit of the mission requirements must be detected, and the external loads must be measured directly. The condition and load levels are then correlated. Usually this correlation can be made during the flight loads program. Due to the placement of the flight loads program at the beginning of the production phase, there can be no validation of the loads analysis until the flight loads program is over. As a result of this time lag, there is a tendency to be conservative in the loads analysis to compensate for possible errors.

However, the problems that arise from designing for error may be worse than the one it is intended to cure. There is the possibility of either type of error in the loads program creating schedule delays and cost over-runs, not to mention the resulting understrength of the structure. In designing for error, a factor is applied to the load that is possibly in error. Here the result is higher weight and thus higher cost. The designer's option is either to ignore the possibility of error in the loads and suffer the possible schedule delays and the possible increased cost or to design for the possible error and pay the price of increased weight and cost. The QSDC Procedure does not ignore the possibility of loads errors, nor does it design for them. The fallacy in designing for error is that the magnitude of the error cannot be known in advance of its occurrence so that the factor applied to the load to account for the error is hypothetical at best. In short, the designer is faced with the problem of how much of an error should the design be accountable for? Obviously, no specific value can be chosen. For example, the designer might decide to account for possible errors in the design by using an "error factor" of 2.0. However, if a decimal point error occurs, this "error factor" would be inadequate. In the QSDC the assumption of the magnitude of the error is recognized as ineffective; consequently, the approach is to be aware of the possible error, monitor the actual operations to detect the possible errors, and redesign if they do occur. This is essentially the practice followed in the Present System.

B.2.2 Strength Errors

Strength errors are defined as those arising when the strength of the structure is less than the strength required to survive the design conditions. The strength required to survive the design conditions will be termed the conditional strength. The conditional strength distribution is the distribution predicted as in Figure B-1. The lower strength distribution is the result of a strength error. An example would be an error in the dimension of a critical part. Suppose that the lower fuselage skin is critically loaded in tension. The strength analysis has shown that a skin thickness of 0.090 inches is sufficient for the design when, in fact, 0.120 inch-sheet is required. As a result, the strength of the 0.090 fuselage skin will be 25 percent less than that required. Similarily, a missing heat-treat note will also create an understrength design. After the fabrication of the prototype structure, the existence of the strength error or understrength design is not known. Unlike the load error, the strength error can be disclosed with a degree of certainty by qualification testing to the design loads that characterize the conditional strength requirement. Thus the qualification test is a conditional strength test, and the reliability demonstrated is a conditional reliability as discussed in References 1 and 5.* The conditions on the reliability are:

1) that the external and internal loads in service are the same as the predicted values in design,

2) that the Limit and Omega Conditions are properly chosen, and

3) that the structure is used in its design mission.

If these conditions are met, then the conditional reliability will be the actual reliability of the structure in service.

The need for testing for the conditional strength requirement has been demonstrated by the Jablecki/Chenoweth data of Figure B-2. Here, the expectancy of failure, in percent, is plotted versus the percent of ultimate load supported. This curve represents the inability of the design analysis to provide the required strength (100 percent ultimate) for the first time static tests. The data also represents qualitatively the ability of the static test to disclose the understrength designs. More recent in published data, Figure B-3 has shown that there has been little improvement in the results of the analysis since the time of the Jablecki/Chenoweth data. These data have been employed in the computer programs of Reference 1 to define the probability that the mean strength of the design, as typified

* All references in Appendix B relate to listing on page 76 in report proper.

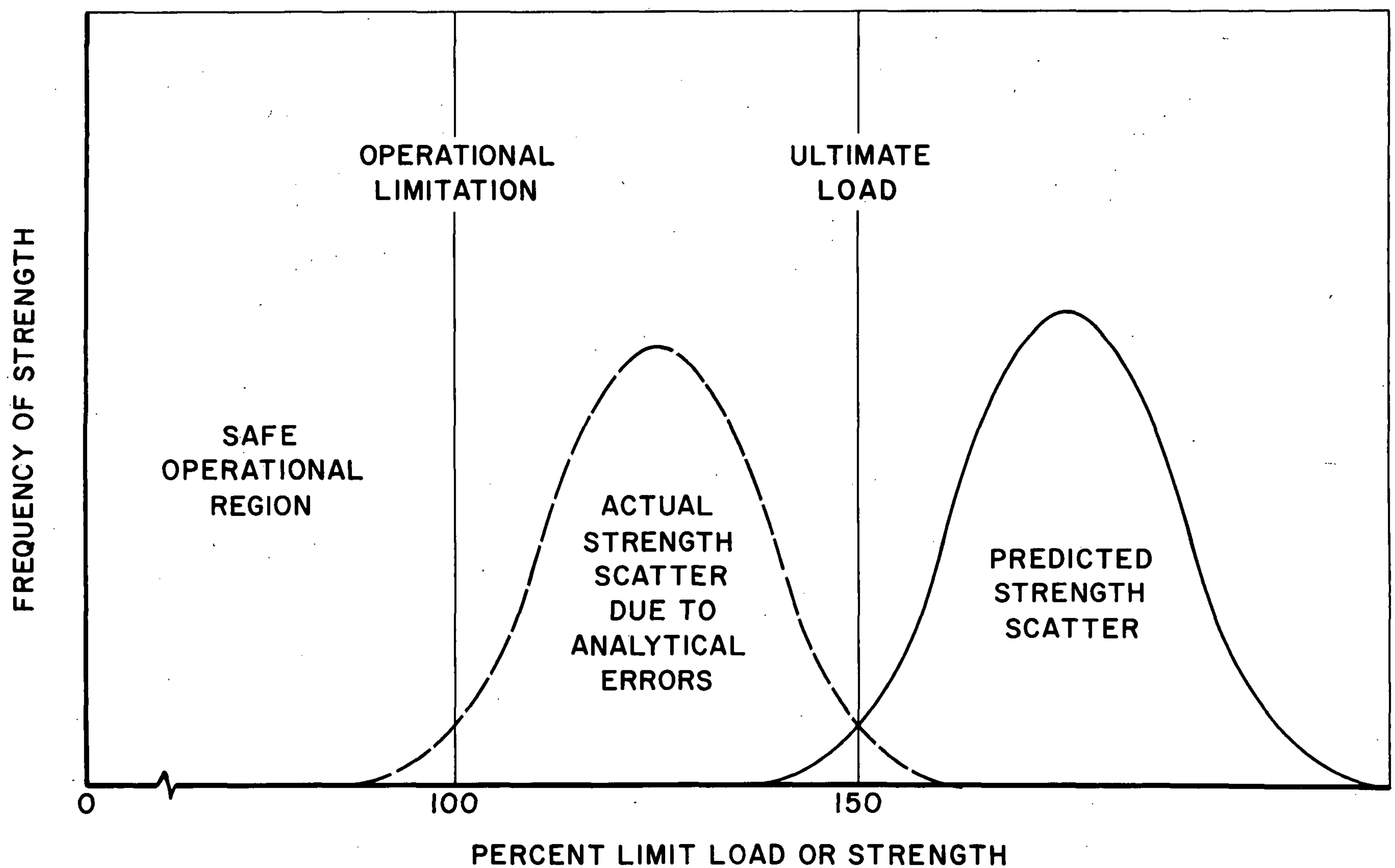


Figure B-1 Effect of Errors on the Strength Distribution as Indicated by the Failure Frequency

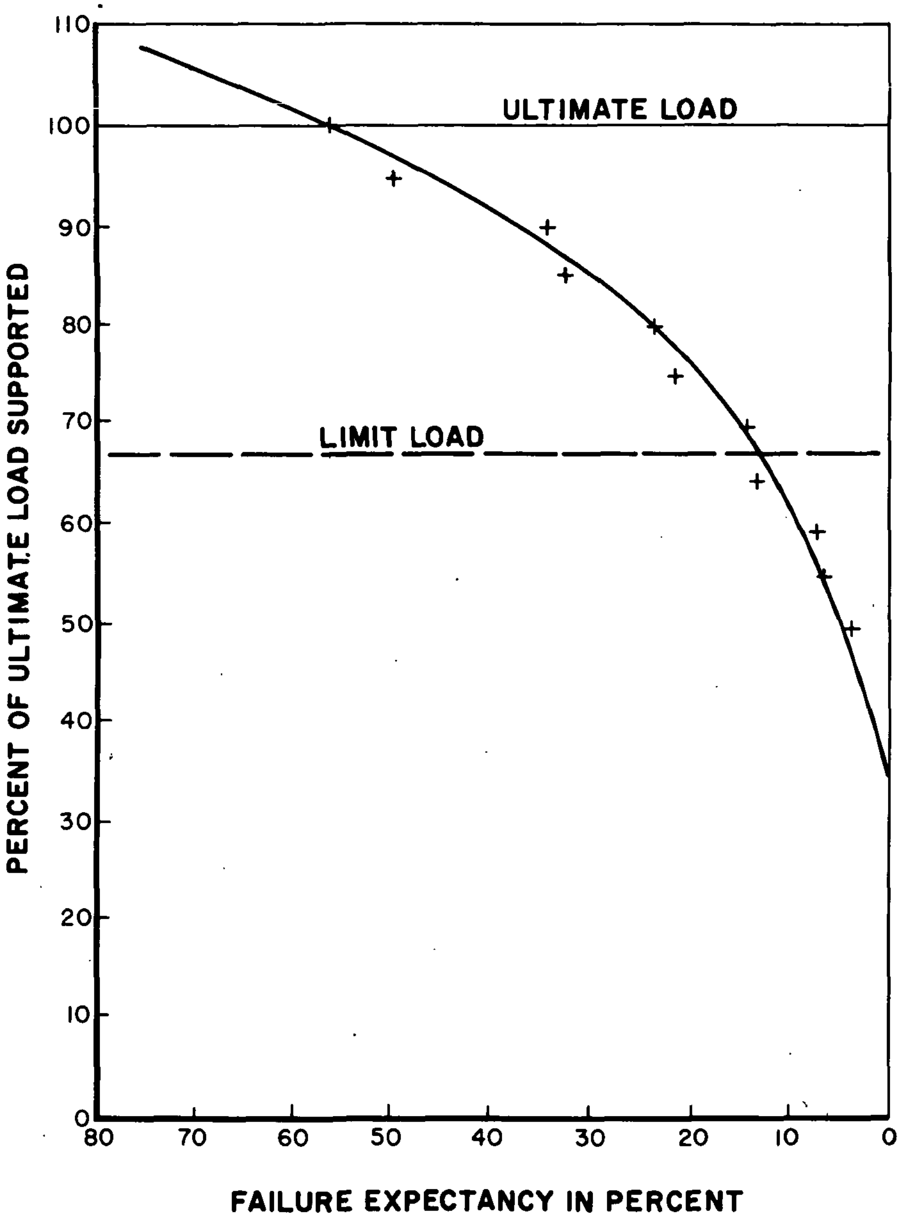


Figure B-2 Jablecki/Chenoweth Data on the Failure of Wing Structures (Reference 3)

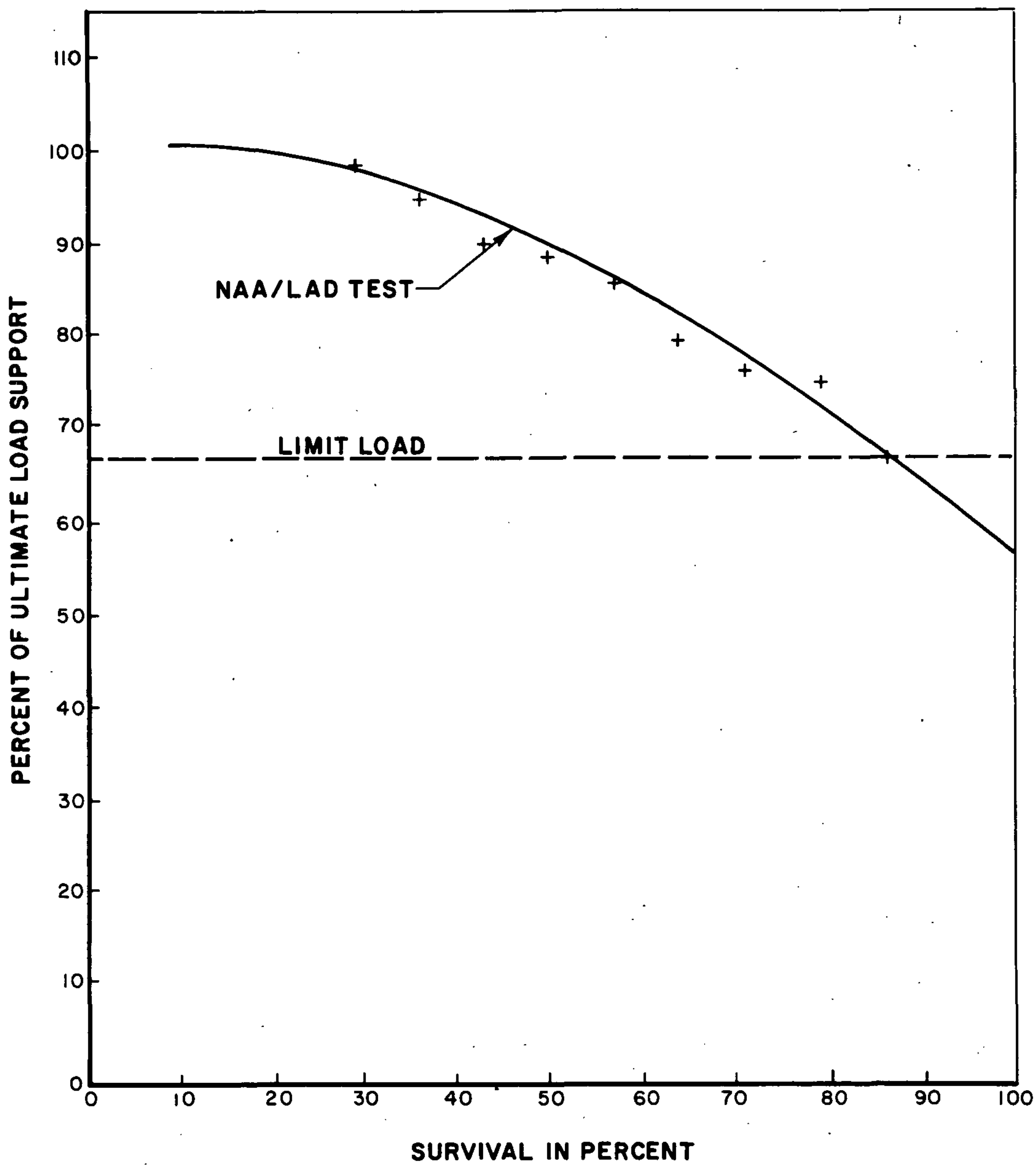


Figure B-3  Unpublished Data on the Failing Loads of Wing Structure in Static Tests (Reference 4) by the test article, is a percentage of the intended design strength. Utilizing this information in the calculation of the reliability of the structure is markedly different from that of other proposed methods where the reliability is presently calculated from the interaction of the tails of the load and strength distributions (Reference 9). In calculating the reliability in this manner, the assumption is made that the location of the strength distribution is known. This is not the real-life situation as evidenced by the Jablecki/Chenoweth data. The real situation indicates that the reliability is much more strongly dependent on the possible location of the actual strength distribution at levels below the predicted value than on the interaction of the tails of the strength and load distributions.