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Residual Life & Strength Estimates of Aircraft Structural Components with MSD/MED

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SUMMARY

Economic and safe operation of the flight vehicles flying beyond their initial design life calls for an indepth structural integrity evaluation of all components with potential for catastrophic damages. Fuselage panels with cracked skin and/or stiffening elements is one such example. A three level analytical approach is developed in this paper to analyse the pressurized fuselage stiffened shell panels with damaged skin or stiffening elements. A Global Finite Element Analysis is first carried out to obtain the load flow pattern through the damaged panel. As an intermediate step, the damaged zone is treated as a spatially 3-Dimensional structure modeled by plate and shell finite elements, with all the neighbouring elements that can alter the stress state at the crack tip. This is followed by the Schwartz-Neumann Alternating Method for local analysis to obtain the relevant crack tip parameters that govern the onset of fracture and the crack growth. The methodology developed is generic in nature and aims at handling a large fraction of problem areas identified by the Industry Committee on Wide-Spread Fatigue Damage.

INTRODUCTION

Structural integrity evaluation of airliners, which have exceeded their initial design life, but are still in operation due to economic constraints, is a major safety concern. After years of service, the micro flaws may have grown and coalesced to form detectable cracks, leading to a scenario called wide spread fatigue damage(WFD). The structural component may have a number of closely spaced small cracks, a situation called Multi-Site Damage (MSD) or a number of small cracks in neighbouring structural elements, a situation called Multi-Element Damage (MED). Although the new aircraft had the required ability to sustain a certain amount of damage, the

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older aircraft with WFD may no longer have the damage tolerance capability necessary to ensure safety. At times, the situation can become catastrophic within two inspection schedules. For continued safe operation, it is desirable to understand the severity of cracks and also have an estimate of residual strength and life of the damaged structure. A reliable damage tolerance assessment requires full scale testing combined with computational analyses. A reliable computational analysis can virtually simulate a test, thus economically predicting its outcome, it can reduce the number of tests that need to be performed. A well established correlation between analyses and a test can help resolve a number of issues which were either missed or could not be extracted during testing.

The *Industry Committee on Widespread Fatigue Damage* has identified about 15 different aircraft structural details that are susceptible to widespread fatigue damage[1]. These include: (1) Longitudinal skin joints, frames, and tear straps (MSD, MED); (2) Circumferential joints and stringers (MSD, MED); (3) Stringer cutouts in frames at successive locations in the fuselage (MED); (4) Aft pressure dome outer ring and dome web splices (MSD, MED); (5) Other pressure bulkhead attachments to the skin (i.e. web attachment to stiffener and pressure decks); (6) Stringer to frame attachments (MED); (7) Window surround structure; (8) Over wing fuselage attachments (MED); (9) Latches and hinges of nonplug doors; (10) Skin at runout of large doubler (MSD) in the fuselage, wing or empennage; (11) Chordwise splices (MSD, MED); (12) Rib to skin attachments; (13) Stringer runout at tank end ribs and (14) Spar cap/web (MSD multiple cross-section). This paper presents a part of an ongoing work dedicated to the development of efficient computational tools, envisioned to involve the least amounts of engineering man power, for structural integrity evaluation of aging, repaired as well as new airplanes. We present a generic methodology developed to assess the residual strength and fatigue life of most of the above mentioned structural components with wide-spread fatigue damage. As a typical illustration of the developed generic methodology this paper presents an investigation of MSD and MED at a stringer - frame junction of a pressurized fuselage stiffened shell panel.

GENERIC METHODOLOGY

In any efficiently designed aircraft sub-structure, the stress flow pattern is fairly complex due to the presence of various stiffening elements, assembled with fasteners in a complex manner. Cracks, any where in the structure, cause further redistribution of stress and overloading of uncracked portion. A single step analytical attempt to understand the damaged substructure with all its intricacies, is not only an inefficient approach but unreliable also. The problem can be efficiently handled through a multilevel analysis, wherein we continously narrow down on the zone under investigation and increase the details in the model, and finally focus on a problem size which can be reliably dealt with well understood fracture mechanics concepts. A three level investigation is sufficient for most of the MSD/MED problems in flight vehicle structures.

Consider the case of damage in an airliner fuselage, essentially a pressurized stiffened shell structure. As a first step, a multibay fuselage panel is analysed. As a second step, a portion of the panel approximately equal to three bays in size is analysed. As a final step the cracked portion is isolated and solved using Schwartz-Neumann Finite Element Alternating Method. The crack tip parameters are then estimated and the corresponding static residual strength is evaluated. By growing the crack and going back through the loop of analyses, residual life is estimated. The details of each of these steps and their integration to form powerful procedures are described in the following subsections.

Global Analysis

The first analysis is done at a level where only a reasonable amount of detail is modeled, the bounds are far off from the damaged zone under consideration and the boundary conditions are either known or can be easily modeled by symmetry/antisymmetry constraints. For the problem of MSD/MED in a fuselage shell structure, a multibay panel with at least two bays on each side of the damaged zone constitutes the global model.

The primary features of the global model are that the skin is modelled as a shell and the frames & stringers are modelled as beams with their neutral axis offset from the shell mid-plane, connected to the shell with a row of flexible fasteners. The shear clips are treated as integrated with the frame beam and the Tear straps are integrated with the shell. Bonded joints, if any, take into account the flexibility of the adhesive.

At this level, the types of damage that can be handled are the cracks in the skin, partially or fully failed stiffening elements such as frames or stringers, partially or fully cracked tear straps, degraded adhesive, broken fasteners and any combination thereof.

The analytical model is a 3-D spatial structure, modeled by 2-D finite elements. The shell is modeled by a 4 noded, 5 degree-of-freedom (dof) per node element, developed by Ashwell and Sabir[2]. The frames and the stringers are modeled by 2 noded, 5 dof, curved and straight beam elements, degenerated from the shell element. The fasteners are modeled by two 2 noded, 2 dof, springs placed orthogonally, with stiffnesses empirically generated using Swift's relationship[3] and 3 multipoint constraints. The damage is taken care of as geometric entities by having disconnected shell/beam elements.

The analysis is carried out by an FEM code developed inhouse, called 'SOFRAC', for damaged stiffened shell structures. The set of input files describing the model and the associated information is generated by a separate preprocessor called 'Multibay Modeler', which draws the information from the geometric and damage database. From the output of the global analysis, the displacements are extracted at the boundaries of the intermediate model.

Intermediate Analysis

At this second stage, the details in the model are refined, the bounds are relatively closer to the damaged zone and the boundary conditions in terms of prescribed displacements are known from the global analysis. For the problem of MSD/MED in a fuselage shell structure limited within about a 5″ length scale, a panel with single frame and three stringers constitutes the intermediate model.

The primary features of the intermediate model are that the skin, frames, stringers, shear clips, and tear straps are all modelled as plates and shells, connected to each other with rows of flexible fasteners. The flanges of the stiffening elements are treated as beams to keep the problem size within limits. Bonded joints, if any, take into account the flexibility of the adhesive.

At this level, the types of damage that can be handled consist of cracks in the skin, frame, stringer, tear strap & shear clip, degraded adhesive, broken fasteners and any combination thereof.

The analytical model is a 3-D spatial structure, modeled by 2-D finite elements. All the plates & beams are modeled by 4 noded & 2 noded, 6 dof elements developed at Lockheed[4]. The fasteners are treated as beams with their section properties tailored to match the empirical behaviour of Swift's fastener. The damage is once again taken care of as geometric entities by having disconnected plate elements.

The analysis is carried out by STAGS(STructural Analysis of General Shells), a code developed at Lockheed, Palo Alto[5]. The set of input files describing the model and the associated information is generated by a separate preprocessor called 'Halfbay Modeler', which draws the information from the geometric & damage database and the displacement output of SOFRAC. From the output of STAGS and its postprocessor STAGSPP, the stresses at the boundaries of the local model and the fastener loads within the local model are extracted.

Local Analysis

At the lowest level, the model is reduced to a rectangular flat sheet with cracks and or holes along the major axis. It may or may not contain the fastener holes. The areas of local model are kept as far as possible from the cracks, with all the other structural details lying outside the rectangle or within the hole. The boundary conditions, in terms of prescribed stresses, at the edges of the rectangular sheet and the surfaces of the holes are known from the intermediate analysis.

The primary feature of the local model is that only a cracked sheet needs to be analysed, into which the influence of the rest of the structure goes as tractions at the boundaries. Concepts of fracture mechanics can now be easily applied to this simple model.

The analytical model is a 2-D spatial structure, modeled by 2-D finite elements. At this stage, we bifurcate into two paths, the inplane and the bending. For inplane analysis, 2 dof, 8 noded isoparametric elements are employed and for bending 3 dof, 4 noded quadratic elements are used.

For the inplane loading situation, the analysis is carried out by a code developed inhouse, based on Finite Element Alternating Method (FEAM) [6]. The input file describing the model is generated by an independent preprocessor called 'Local Modeler', which draws the information from the output of STAGSPP and Halfbay Modeler. For the bending part of the analysis, the FEAM code is under development. The outcome of these analyses is the crack tip parameters which can be used to determine the residual strength of the structure and crack growth rates of all the cracks. The cracks can be grown at this level, under fatigue loading, upto a stage where they either linkup or start influencing the edge tractions evaluated during intermediate analysis.

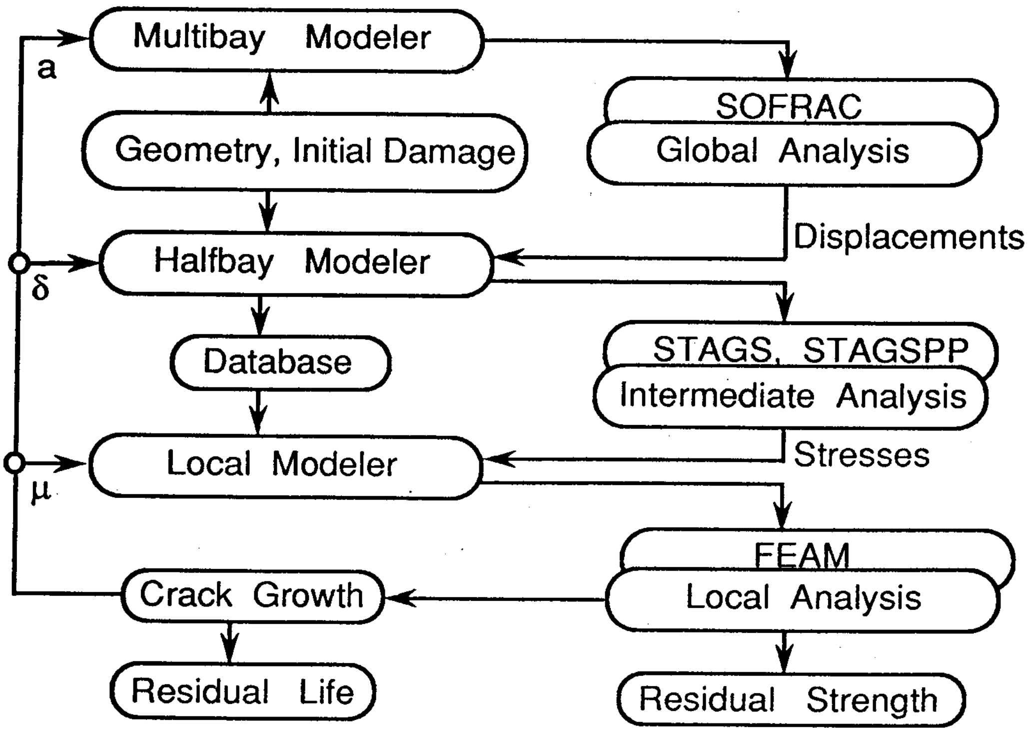

Figure 1: Computational procedure for analysis of MSD in structures.

At this stage, the damage configuration needs to be updated in the intermediate model. Net ligament yielding is considered as the linkup criterion[7].

The next three subsections describe how these modules viz., Multibay Modeler, SOFRAC, Halfbay Modeler, STAGS, Local Modeler, FEAM can be integrated in different architectures and the information can be made to flow between them so as to assess the residual strength and residual life of structural components with MSD and/or MED.

Analysis of Multi-Site Damage

For the analysis of structural components with MSD, figure 1 describes the computational procedure. Starting from the geometric and the initial damage database, the Multibay modeler generates the global model that is fed into the SOFRAC for global analysis. The Halfbay modeler generates the finite element model based on same initial geometric and damage information, with boundary conditions as prescribed displacements, extracted from the solution of SOFRAC. At this stage, another set of files is also written, containing information necessary to post process the output of STAGSPP and generate the local model. The local modeler picks up the necessary information from the output of Halfbay Modeler and STAGSPP, generates the local model and feeds into the FEAM. The FEAM code is capable of handling multiple cracks of arbitrary lengths. This local analysis gives the cracktip parameters for multiple cracks, which are now used to estimate the residual strength and crack growth rates. The cracks are grown

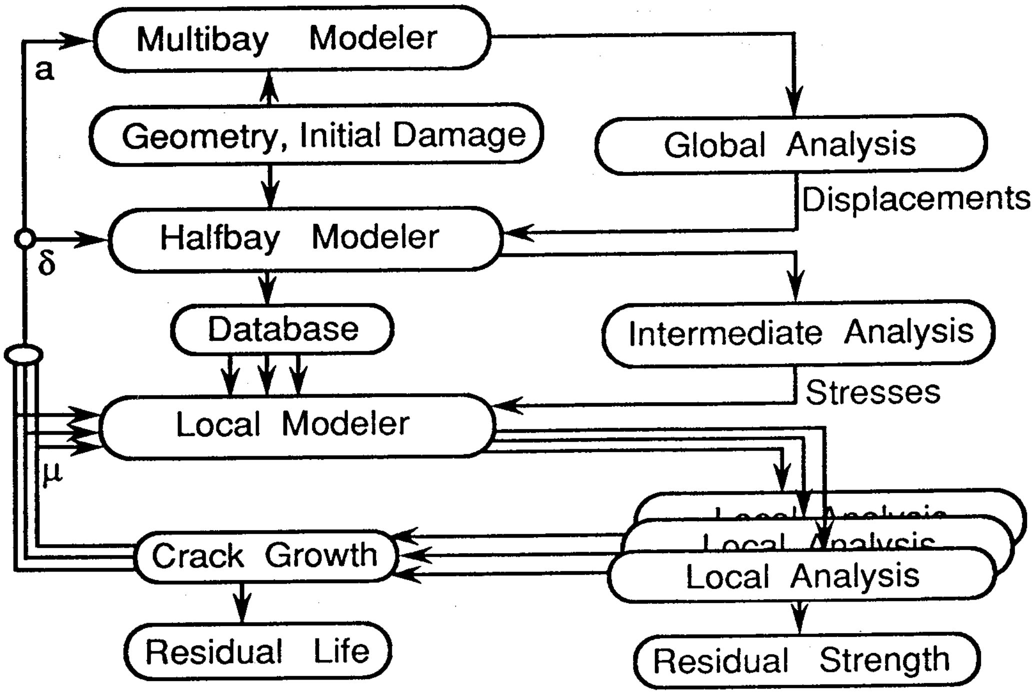

Figure 2: Computational procedure for analysis of MED in structures.

at this stage with net ligament yield as the linkup criterion(Research is now being completed to use T^* as the link-u[p criterion [8]). For very small crack growth, local analysis is performed with updated damage information. If the crack growth is large or a crack linkup occurs, the damage is updated at the intermediate analysis level. For substantial crack growths, the global analysis is redone. This procedure simulates the crack growth and provides with information about residual life. Experience has shown that for every 5 stages of local analysis, intermediate analysis needs to be done and for every 5 stages at intermediate analysis (25 local analyses), there is a requiremenet for a fresh global analysis.

Analysis of Multi-Element Damage

The modular nature of the subprocedures and their interfacing through regular ASCII files lends itself to various possibilities. One of them is the handling of structural components with MED. The Halfbay Modeler generates database for multiple local analyses, each local zone covering a damage which can be a single crack or an MSD. The Local Modeler generates multiple models and these can now be analysed independently, using FEAM. The cracks are grown in each of these analyses independently. Whenever required, the Halfbay Modeler can integrate the current damage configuration and perform fresh intermediate analysis. Figure 2 explains this procedure pictorially. The methodology at and above the level of intermediate analysis in the hierarchy remains same as before. Since the FEAM local analyses can handle multiple cracks,

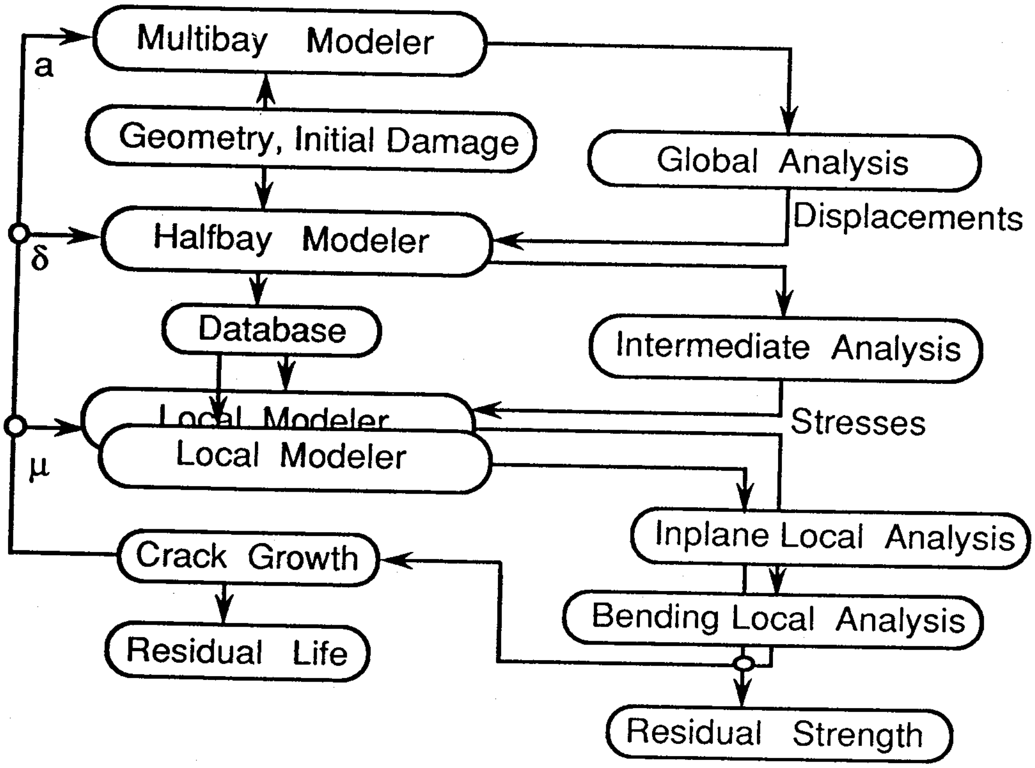

Figure 3: Computational procedure for analysis of MSD/MED with significant bending.

this procedure has the power to resolve situations where MSD exists in neighbouring elements, viz., MSD as a subset of MED.

Analysis of Problems with Bending

For the analysis at the local level, if there is a significant bending involved, the Halfbay Modeler can generate two sets of information, one for inplane and one for bending problems. The local modeler will generate two models which will go independently into two different Finite Element Alternating codes. The crack tip parameters for the two loading situations will then be integrated to evaluate the residual strength and the crack growth rates. This methodology, presented in figure 3, depends upon FEAM for cracked plate bending problems, which is under development.

The power of all these procedures emerges from the fact that a wide range of problems with widespread fatigue damage can be handled. Multiple cracks can be grown irrespective of where they are in the substructure. The efficiency has been achieved by automating the procedures to an extent where more than half a dozen modules work from a single set of initially generated input files.

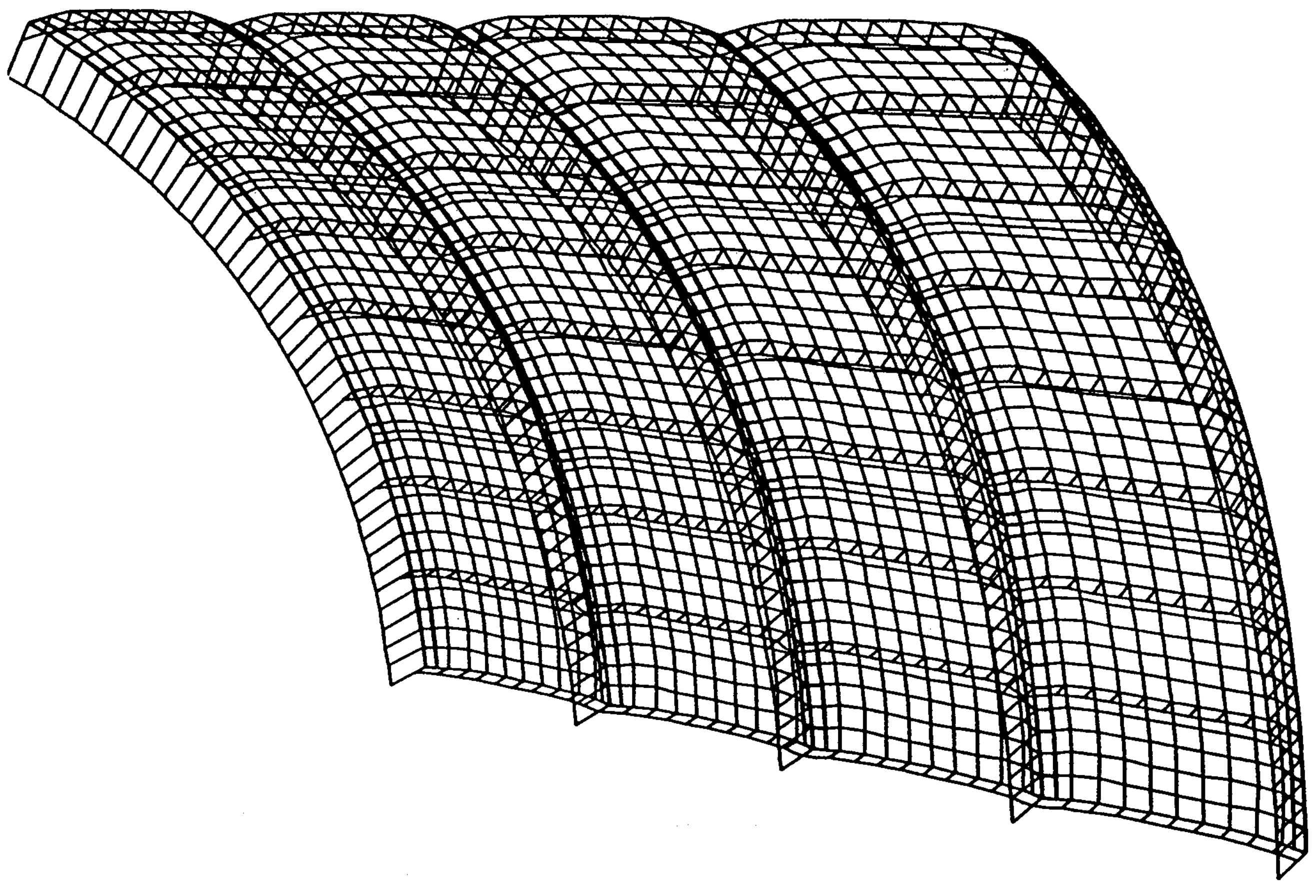

Figure 4: Deformed view of the global model of 4×8 bays of fuselage panel.

AN EXAMPLE PROBLEM

We now employ the above described methodologies to analyse a situation of MSD and MED at the frame stringer junction in a typical narrow body fuselage panel. This example is only intended to demonstrate the potential of the developed computational procedure.

Configuration

Consider an airliner fuselage formed by 0.036″ thick, Al 2024-T3 shell, of radius 74″ and stiffened by 'Z' section frames 20″ apart, 2″ × 0.036″ tear straps at each frame location and 'Z' section stringers 9.25″ apart, all of them attached with fasteners, 5/32″ in diameter spaced at 1″. The stringers run through the cutout in the 'L' section shear clips which attach the frames to the skin through the tear strap. The internal pressure in the fuselage is 9.0 psi.

For the purpose of global analysis, we consider a multibay panel of 5 frames and 9 stringers. A typical deformed finite element model from SOFRAC (approx 15,000 degrees of freedom, magnification = 5) is shown in figure 4. On an HP workstation 7000 900 series, the CPU time for the problem of this size is about 10 minutes.

For an intermediate analysis, a section of this consisting of a single frame, shear clip & tear strap and 3 stringers is modelled. Figure 5 shows an exploded view of a typical deformed FE model (approx 20,000 dof, magnification = 5). This problem takes about 15 minutes on an HP workstation.

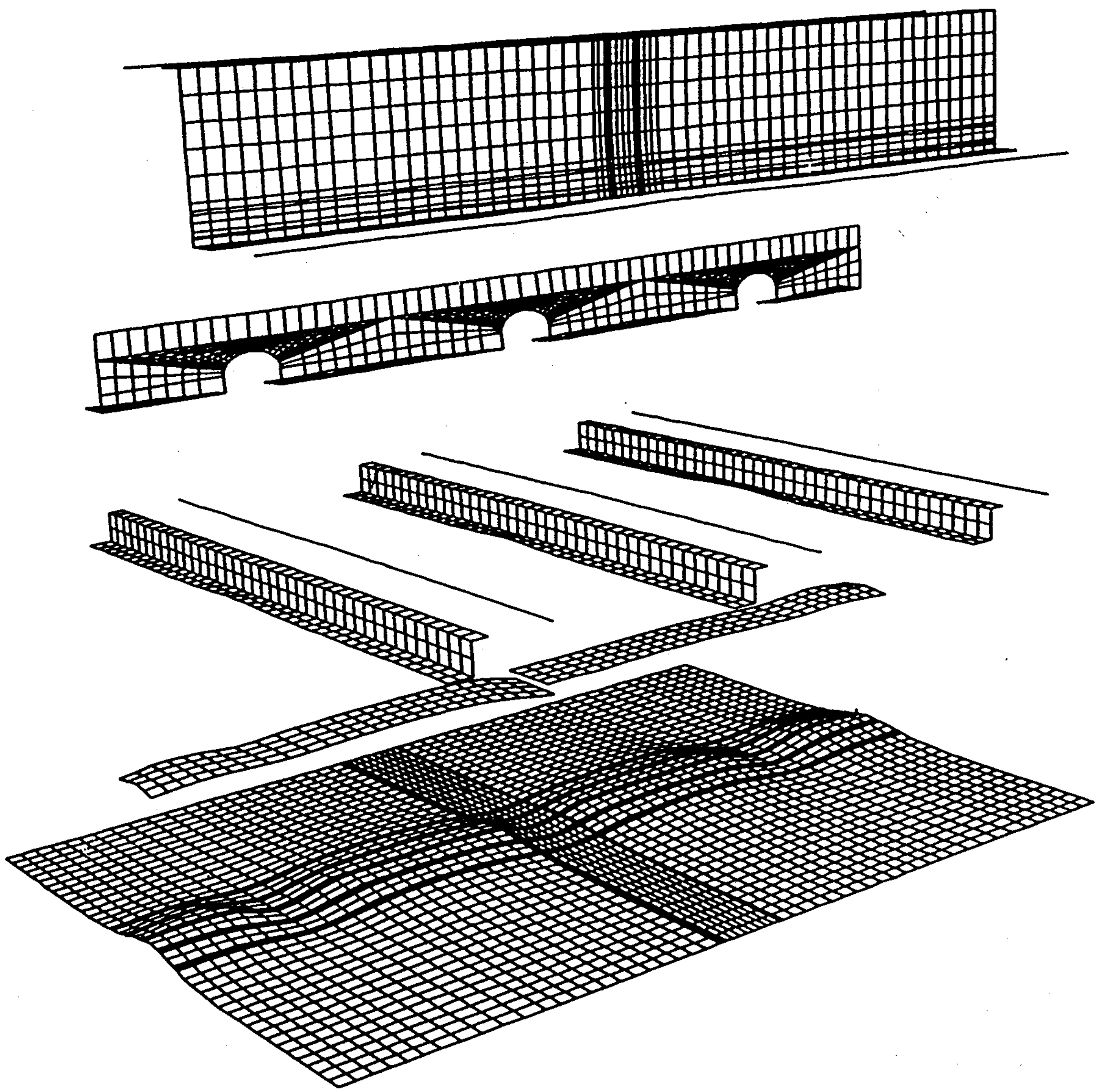

Figure 5: Exploded deformed view of the intermediate model of 1 × 3 bays of fuselage panel.

The local model consists of a flat rectangular cracked sheet and depends upon the type of damage being analysed. It takes approximately 3 minutes per crack tip for the local analysis to be complete. The damage is considered in various forms and is categorized in the following three sets.

Multi-Site Damage in the Skin

Consider the situation of an MSD cracking in the skin at the row of fasteners joining the skin and the central stringer. Let the initial crack configuration consist of 5 cracks of length 0.125″ on both sides of the fasteners, along the row of fasteners, at a location directly below the central frame. This location is marked by 'A' in figure 5. This situation was run through the procedure of figure 1 and it was found that the first linkup of cracks occurs at 8,920 fuselage pressurization cycles. The same MSD situation was analysed with the tear strap fully cracked at the same location. The type of the damage considered in the tear strap is apparent from the figure 5. The effect of broken strap is to reduce the life to only 2,518 cycles (about 28%). This analysis is presented graphically in figure 6. The analysis is carried out only upto first linkup as it has earlier been observed [9] that the first linkup is virtually the end of the life of a panel with MSD. A lot of other damage scenarios with MSD can also be analysed in a similar manner.

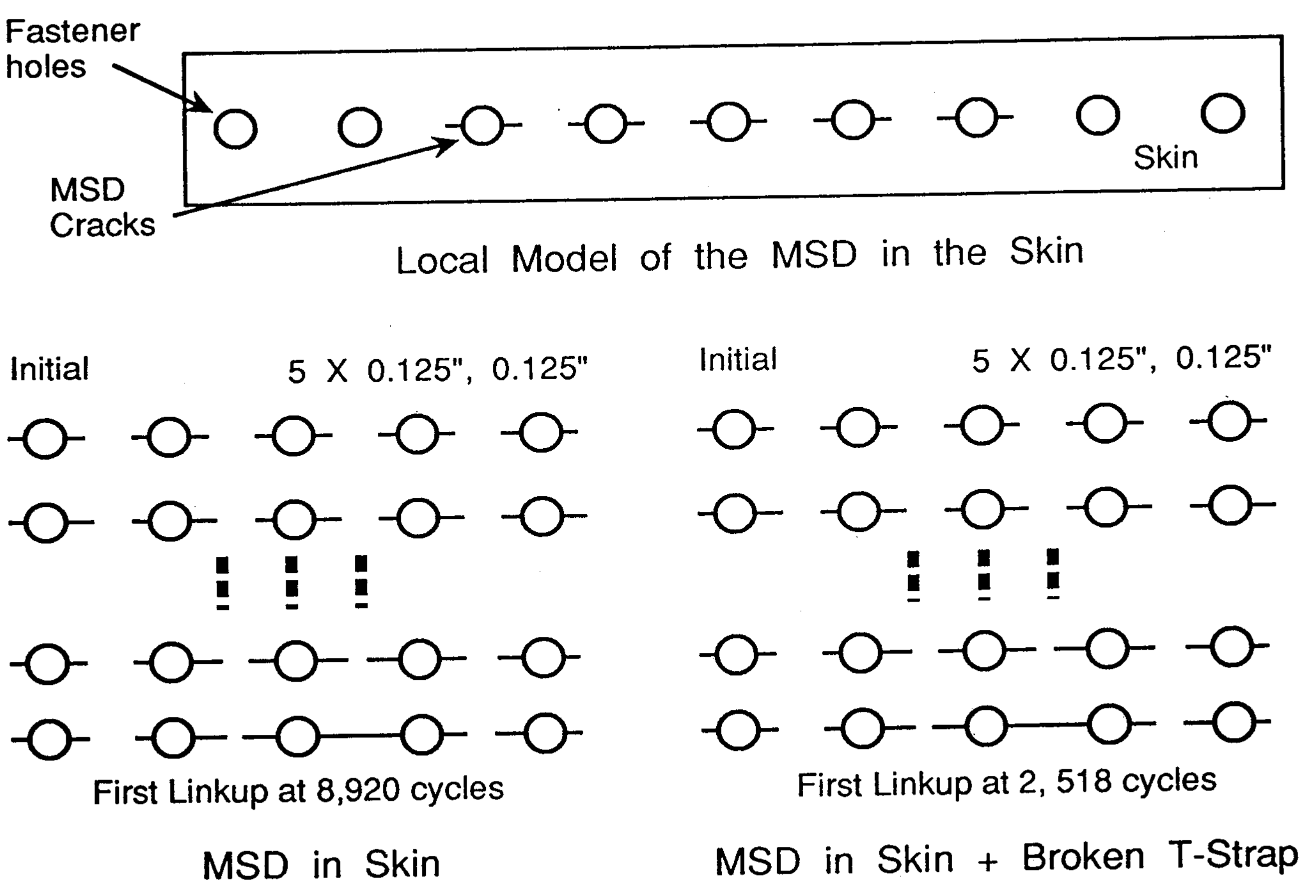

Figure 6: Analysis of MSD in the skin.

C-4.

A Crack in the Frame

Consider the situation of a single crack in the frame, emanating from a fastener, running normal to the row of fasteners joining the frame and the shear clip, located directly above the cutout in the clip through which the central stringer runs. This location is marked by 'B' in figure 5. Initially, let the crack lengths be 0.122″ & 0.228″ respectively towards & away from the shear clip. The crack lengths are measured from the hole center to the crack tip, and have been chosen arbitrarily. The fatigue analysis is done, as per the procedure described in figure 1, upto a situation where the plastic zone size ahead of the lower crack tip (towards the shear clip) touches the flange of the frame. This corresponds to a crack length of about 0.372″. The scenario is presented in figure 7.

The above described growth of the crack is found to take 451,811 cycles of fuselage pressurization. But the situation gets suddenly worse if any of the other stiffening elements are damaged. The same crack grows about 100 times faster with a broken tear strap, about 200 times faster with a broken shear clip, about 1600 times faster with both strap and clip broken. Cracking in the skin further speeds up the crack growth. This is presented in table 1. Although, in actual case, the MSD or the lead crack in the skin will grow as the crack in the frame grows, but that is not modelled in this particular example, and is looked at in the following subsection.

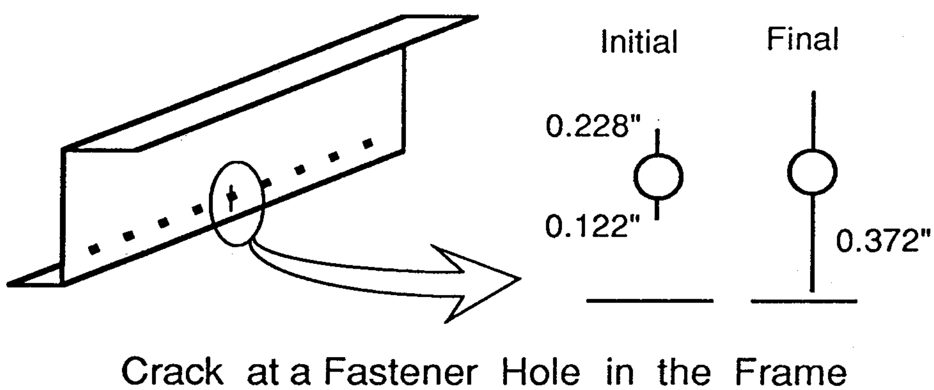

Figure 7: Analysis of a single crack in the frame.

Table 1: Effect of damaged elements on crack growth in frame

Tear strap	Shear Clip	Skin	Cycles
intact	intact	intact	451,811
broken	intact	intact	4,476
intact	broken	intact	2,172
broken	broken	intact	284
broken	broken	MSD	268
broken	broken	5″ crack	84

Multi-Site Damage in the Skin and a Crack in the Frame

Consider now a situation of Multi-Element Damage with a crack in the frame, MSD in the skin and a broken tear strap. The initial crack configuration corresponds to the combination of initial MSD situation with a fully cracked tear strap and the initial crack configuration in the frame analysed in the previous two subsections. The MSD cracking in the skin and the crack in the frame are grown by running two independent models at the local level, as described in figure 2. The first linkup of MSD in the skin occurs at 2,212 cycles. The analysis is stopped at this stage. Comparing this with results of figure 6, the crack in the frame speeds up the MSD crack growth by about 12%. In the mean time the lower crack in the frame had grown to a length of 0.354″, as shown in figure 8. For the problem in the previous subsection, the crack in the frame had grown to this length in 2,396 cycles. This implies that the MSD in the skin speeds up the crack in the frame by about 8%. Thus both MSD in the skin and the crack in the frame are found to speed up each other's growth.

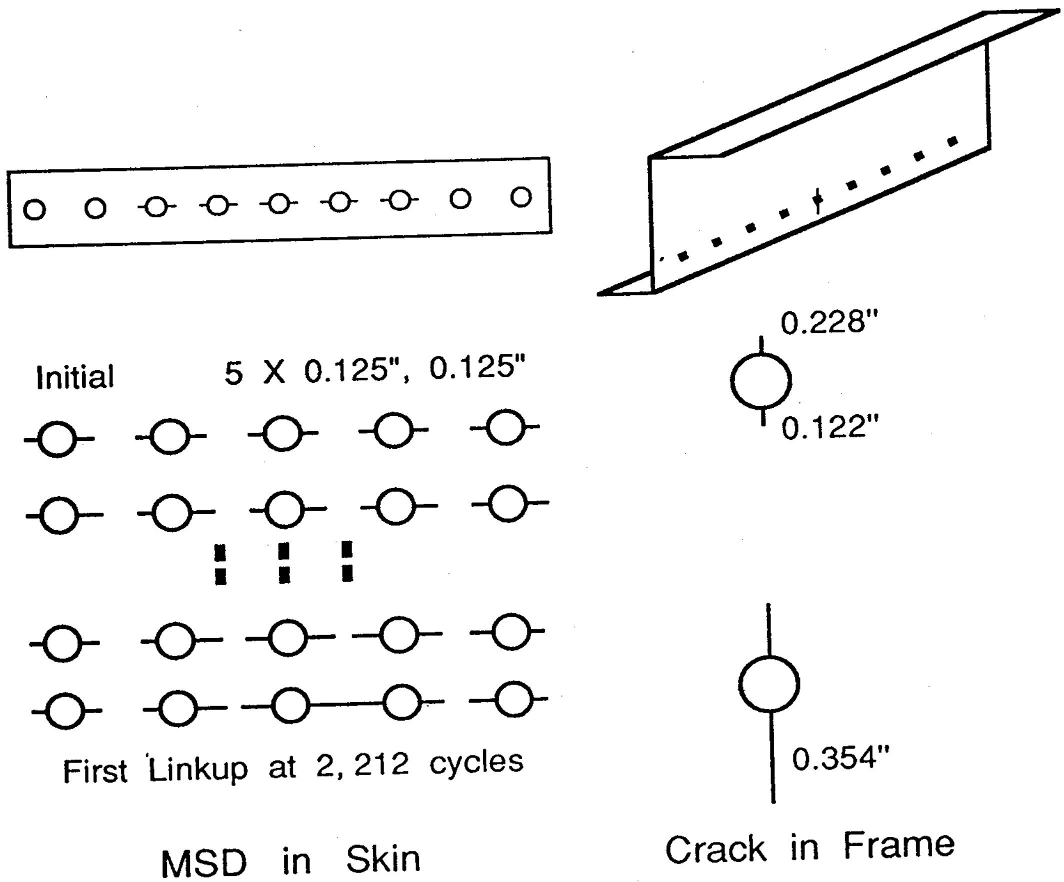

Figure 8: Analysis of MED in the skin and the frame.

The above set of examples were analysed in less than 24 computer-man hours. This shows the power and efficiency of the developed procedures.

CONCLUSION

A very powerfull and an extremely efficient computational procedure/tool has been developed, by combining the alternating technique, hierarchical finite element strategy and automatic modelling & execution. The potentials of this methodology have been demonstrated through an example of Multi-Site and Multi-Element Damage in a fuselage panel.

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