Data Reduction and Its Impact on Test-Analysis Correlation

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Abstract

A research project has been initiated to improve crash test and analysis correlation. The research has focused on two specimen types: simple metallic beams and plates; and a representative composite fuselage section. Impact tests were performed under carefully controlled conditions. In addition, the specimens were densely instrumented to enable not only correlation with finite element simulations, but to also assess the repeatability of the data. Simulations utilizing a detailed finite element model were executed in a nonlinear transient dynamic code. The results presented in this paper concentrate on the effect of several data reduction processes, to include filtering frequency and sampling rate, on the correlation accuracy.

Introduction

In the last decade significant advances have occurred in finite element simulation of crash energy management and in experimental data acquisition systems. For example, full-scale crash simulations performed with nonlinear, transient dynamic, finite element codes can incorporate structural complexities such as: geometrically accurate models; human occupant models; and advanced material models to include nonlinear stress-strain behaviors, laminated composites, and material failure. Development of these detailed finite element models and analysis of the simulation results require investment in substantially skilled analysts and computer resources. However, schedule and budget constraints often force analysts to minimize efforts to analyze and correlate the results with experimental data. Often, the assessment of the correlation accuracy is based on the comparison of parameters such as crash pulse duration and peak or mean acceleration of the large masses. These parameters provide valuable information with regard to the global response of the aircraft.

A project was initiated through the NASA Aviation Safety Program to better quantify the accuracy of crash simulation results. The motivation for the project is: to document modeling improvements; to evaluate design configurations analytically; and to enable certification or qualification by analysis. The primary objective of the project is to evaluate several methodologies for application to the correlation of crash finite element model results with measured crash data.

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The research presented in this paper is based on the need to better quantify the accuracy of crash simulation results generated by nonlinear, transient dynamic, finite element codes. Specifically, this paper will concentrate on the effect of data reduction processes on the assessment of correlation accuracy. These data reduction processes included the filtering frequency and sampling rate. Additional details regarding the research project have been published in Refs. [1] and [2].

Background

The difficulties in correlating test and analysis results are compounded by the increasing use of crash simulations utilizing detailed finite element models. The kinematic approaches developed in the 1970 s and 1980 s use models that are generally composed of less than 100 elements (concentrated masses, beams and crush springs). Kinematic models, such as that shown in Figure 1, have traditionally been used to develop predictions of the gross responses of the aircraft with respect to the performance parameters of energy-absorbing components, recovering loads that can be used for sizing of structures, and other useful functions. Simplification of the complex structure of an aircraft to less than 100 elements requires significant engineering judgement and numerous approximations. Current modeling capabilities enable analysts to construct detailed finite element models with accurate geometric and material property information. Detailed crash finite element models, such as that shown in Figure 2, are solved with nonlinear, transient dynamic, finite element codes, for example, MSC.Dytran, Ref. [3]. These models are considerably more complex, but have the ability to directly predict structural performance, human response, and performance of energy-absorbing structures. The details allow inclusion of complex failure behavior in the material property specifications. This attention to the structural details will allow prediction of not only the large mass accelerations, but also simulation of primary and secondary structural responses. The effective utilization of the detailed finite element approach is dependent on the ability to systematically and efficiently reduce, evaluate and correlate large amounts of data. As stated in the Introduction, one of the primary motivations for the project was to enable the documentation of modeling improvements resulting from the use of detailed crash finite element models.

Two types of structur es are being employed in the evaluation of the correlation methodologies, they are: simple metallic beam and plate structures; and a representative advanced-concept, composite fuselage section. The beam and plate efforts are intended to allow evaluation of analysis techniques on very simple structures. The techniques deemed viable from the simpler structural applications are then applied to the fuselage section. The fuselage section results enable evaluation of these techniques on a more realistic structure. The examples presented in this paper are from the fuselage section results. However similar results and concerns were evident for the simple metallic specimens.

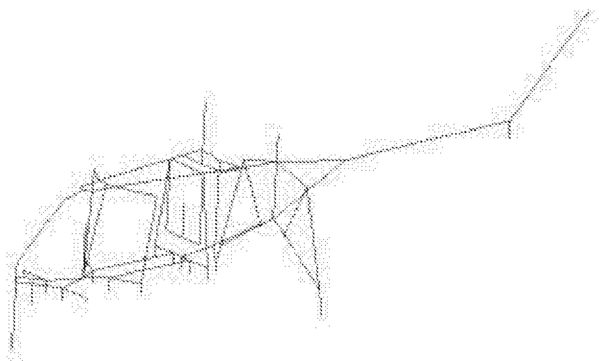

Figure 1. Example kinematic model.

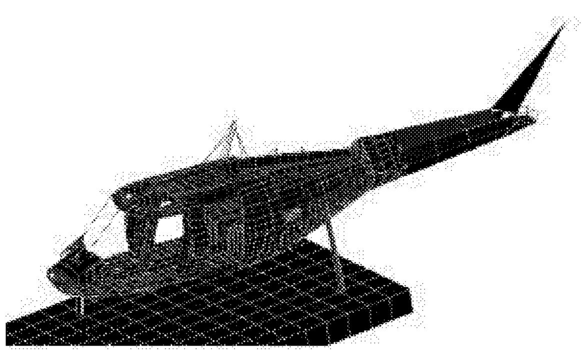

Figure 2. Example detailed finite element model.

Description of simple metallic tests

An overview of the metallic specimen testing will be summarized. The test matrix for the beam specimens includes variation of parameters such as steel vs. aluminum; flat vs. T-section; pinned-roller vs. pinned-pinned. The plate specimens address the variability of material property and stiffener configurations.

The test fixture, see Figure 3, is designed to be substantially stronger and stiffer than the specimens tested. For isolation, the test fixture is mounted on a concrete block that is 36 in. in diameter and 13 in. in height. This concrete block is then leveled in a bed of sand. The 16-lb. semi-cylindrical impactor glides up and down the impactor guide. The guide and the polyethylene corners on the impactor properly position the impactor to deliver precise and repeatable impacts as required, yet minimizes sliding friction as the impactor falls through the guide tube.

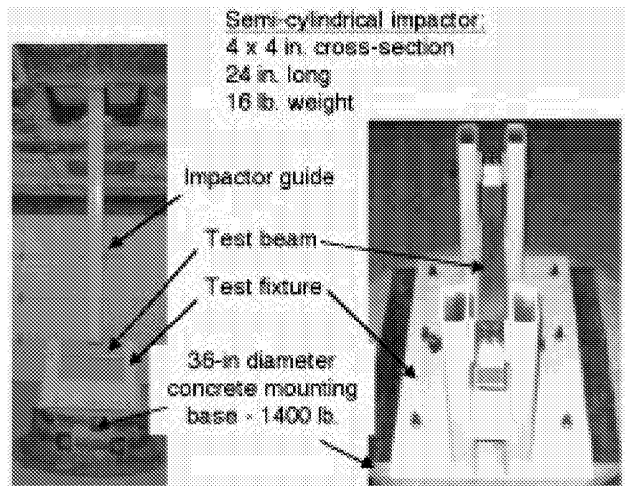

Figure 3. Metallic structure test set-up.

For the configuration shown in Figure 3, the beam is 24 in. in length from pin to pin. Transducers are placed at +/- 4 in. and +/- 8 in from the beam center to achieve symmetric instrumentation. The strain gages are on the upper surface and accelerometers are on the lower surface of the beam.

Description of fuselage section test

An advanced-concept, composite full-scale fuselage aircraft section with an energy absorbing subfloor, see Figure 4, was recently impact tested at the NASA Langley IDRF, Ref. [4]. The purpose of the test was to acquire a high quality and detailed data set for use in the test and analysis correlation project. The fuselage section was selected for several reasons. Extensive experience in both modeling and testing of the section has been gained over the past 4 years, Refs. [5] and [6]. This experience enabled the authors to concentrate on the evaluation of correlation practices rather than devote significant resources to structural design, finite element model development, and test preparation. In addition, the structure was considerably more complex than the simple metallic structures. This complexity allows the evaluation of several techniques on a more realistic structure.

The fuselage section is 64 in. long with a diameter of 60 in. The design includes a very stiff floor that produces an essentially uniform global crushing of the energy absorbing subfloor. Details regarding the fuselage section design and previous tests are documented in Ref. [5]. In the current configuration, the fuselage section contained ten 100-lb. lead weights symmetrically distributed on the fuselage floor, see Figure 5. The weights were attached to the section through bolts connected to the seat rails.

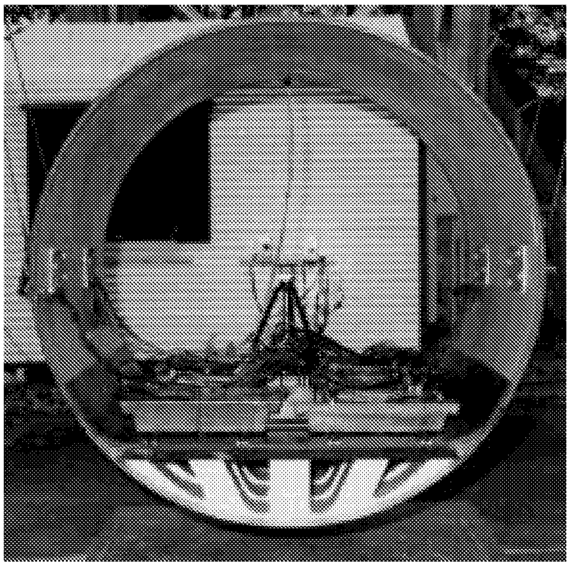

Figure 4. Photograph of fuselage section.

Numerous video and high-speed film cameras as well as still cameras recorded the test. In addition, data were recorded from 73 accelerometers at 10 kHz sampling rate by an on-board digital data acquisition system. Only the floor accelerations indicated in Figure 5 are of interest in this paper. Additional details can be found in References [1] and [2]. Figure 6 shows a close-up of the instrumentation details. The instrumentation layout was designed to evaluate among other things, the effect of mounting mass on the accelerometer response. Optimal placement of instrumentation is frequently not feasible for full-scale testing. Location **A** is considered to be an ideal location for determining the floor accelerations directly input at the seat leg. The weights have been installed to grossly approximate the point loads caused by incorporation of seats. The 100-lb. weight has been modeled as two 50-lb. concentrated weights on each seat rail in the finite element model. Location **B** is typical of many applications where the accelerometer is placed on a mounting block on the seat rail, but near the seat leg attachment point. The accelerometer location has been incorporated into the model as the weight of the accelerometer and associated mounting block, or 1/3-lb. weight. The final location, **C**, is that for an accelerometer placed on a 1-inch aluminum cube directly adhered to the floor. This was modeled in the limit as no additional weight at that node.

The desired impact conditions were 300 in/s vertical velocity, no roll, pitch or yaw. The true impact conditions varied slightly from these values. As the predictions were intended to be a priori, the roll, pitch and yaw in the simulations remained at zero.

The test conditions and instrumentation were designed for correlation with a finite element simulation rather than for simply evaluation of a crashworthy concept. For this reason, the fuselage section was densely instrumented. Correlation of the high channel count was feasible due to the streamlining of the data reduction process. In addition, the impact attitude and velocity were set to avoid catastrophic failures. In this case it was desired to crush the subfloor without damaging the upper structure. Testing structures to evaluate the ultimate strength is important, although correlating the data from these tests with finite element simulations is extremely difficult. Questions arise as to the accuracy of the data and occurrence of failures. These unknowns result in qualitative comparisons, with several qualifications accompanying the comparisons indicating the number of unknown and unresolved issues.

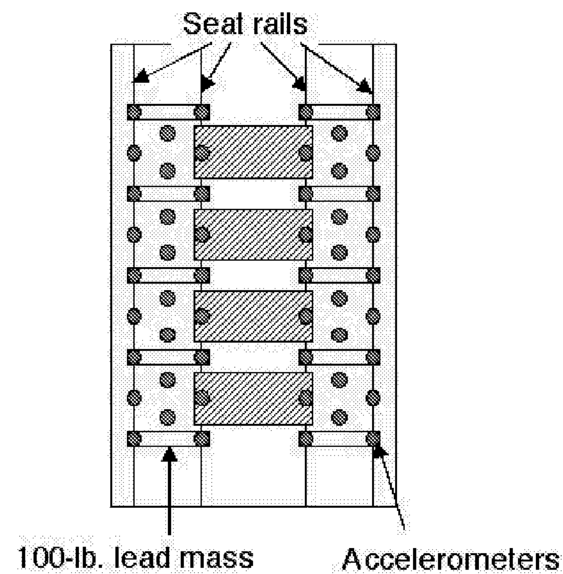

Figure 5.Schematic of section floor with instrumentation.

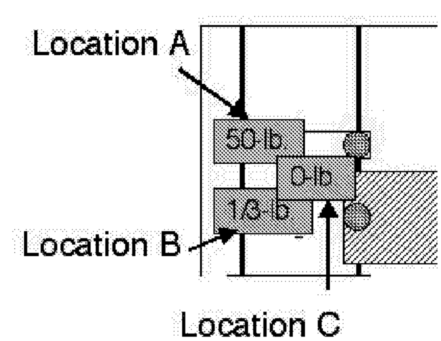

Figure 6. Detailed view of instrumentation placement.

Before correlating with simulation results, extensive and detailed analyses of the data were performed. These analyses were intended to insure that sufficient data existed to evaluate trends. In addition, the volume of data acquired proved valuable for identifying similarities and anomalies in the results. The analyses utilized the symmetry of the test structure and desired impact condition.

Based on the findings from the extensive data evaluations, the experimental data is considered to be of sufficiently high quality to adequately evaluate, as well as to guide the development of the correlation methodologies.

Description of section finite element model

The finite element model is shown in Figure 7. The model is comprised of approximately 30,000 elements and 30,000 nodes. The stiff structural floor was modeled as two laminated composite face sheets with a foam core. The foam core is represented using solid elements assigned linear elastic material properties. The composite face sheets are represented with linear elastic orthotropic material properties. The upper section is also modeled with a foam core with laminated composite orthotropic face sheets. The subfloor section has solid elements with orthotropic face sheets on the interior surfaces. The accuracy of the crash simulations for this model is directly dependent on the accuracy of the subfloor foam material properties. A stress-strain table was supplied for the FOAM2 material properties in the model. Additional details regarding the modeling approach are found in Ref. [5].

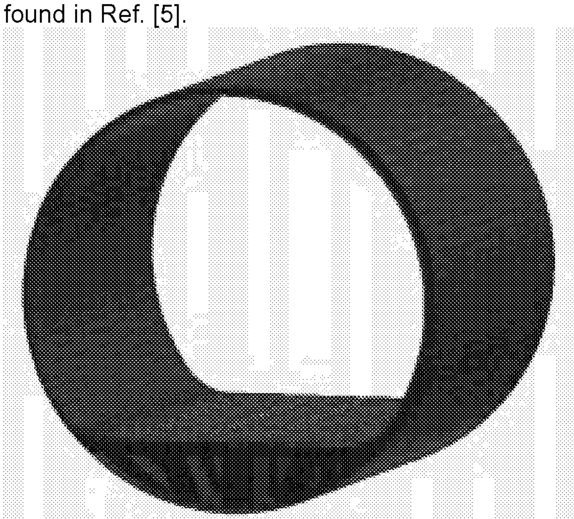

Figure 7. Schematic of fuselage finite element model.

Results

The variations of measured accelerations for essentially symmetric locations are shown in Figure 8 and 9, when low-pass filtered at 100 Hz and 24 Hz, respectively. The curves have been color-coded as indicated in schematics. Location **B** was selected because it closely represents an accelerometer location found in full-scale crash testing. In Figure 8, the variation as a function of time is as much as 40 %. This is due in part to the slight pitch angle as well as structural anomalies. The filter cut-off frequency of 100 Hz was selected as this is the lowest of the possible filtering frequencies or Channel Frequency Class specified in SAE J211, Ref. [7]. The variation in peak and mean accelerations is substantially less at 3.6 g and 0.8 g, respectively. Note that the mean was computed from 0 to 0.05 s. The value of the mean is strongly dependent on the selected time duration, as expected. The same data when filtered at 24 Hz is substantially smoothed, however significant variations still exist. A filter cut-off frequency of 24 Hz was selected to smooth oscillations and highlight the global response. The maximum acceleration varies by 1.1 g and the mean by 0.7 g. These experimental variations for essentially symmetric locations have been presented to highlight the variations that occur for real structures under carefully controlled experimental conditions.

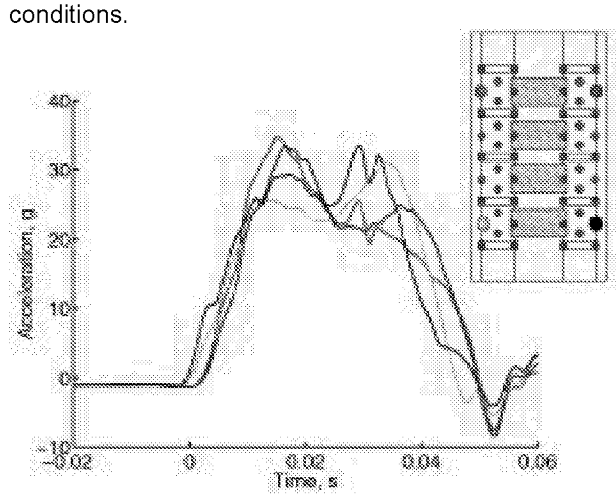

Figure 8. Variation of measured accelerations for symmetric locations (Filtered at 100 Hz).

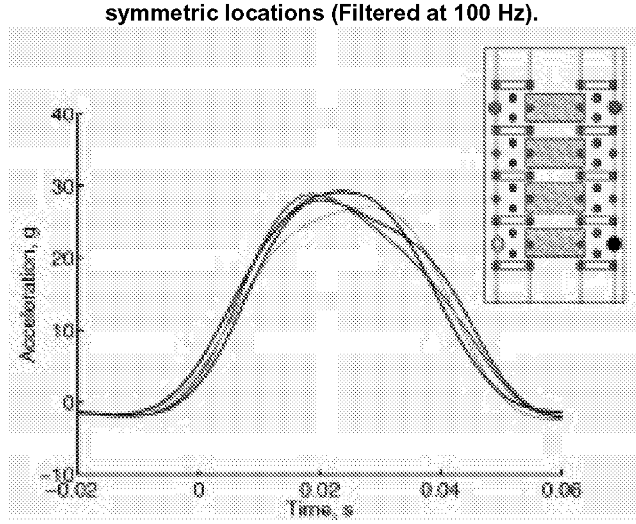

Figure 9. Variation of measured accelerations for symmetric locations (Filtered at 24 Hz).

The effect of accelerometer placement was studied. Correlations of measured and predicted accelerations are presented in Figures 10-12 for the 3 types of accelerometer placement. To facilitate the data reduction process, the simulation results were also sampled at 10 kHz. Note that the agreement between measured and predicted results is reasonable for Locations **A** and **B**, Figures 10 and 11, respectively. However, gross disagreement is shown for Location **C** in Figure 12. An extensive investigation was required to determine the cause of the discrepancy. The fuselage section has been designed to globally crush the subfloor with little spatial variation of the global motion. This uniform global motion was evident in the test video as well as deformed plots of the simulation model. Therefore, the predicted results for Location **C** were not readily understood.

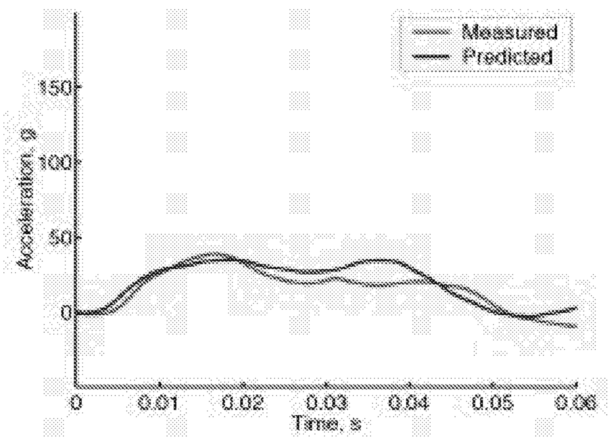

Figure 10. Comparison of measured and predicted accelerations at Location A.

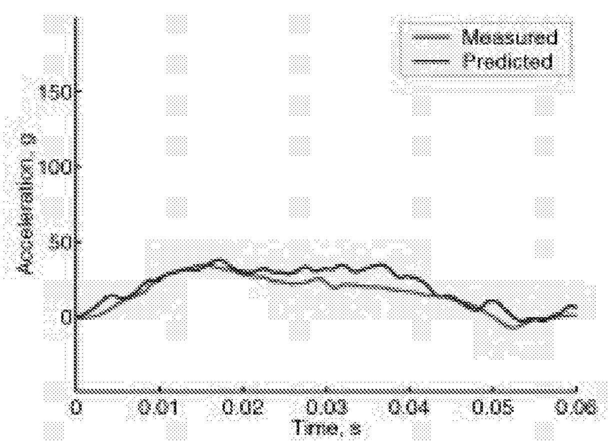

Figure 11. Comparison of measured and predicted accelerations at Location B.

To insure that the discrepancy did not result from the filtering process, an evaluation of the unfiltered velocities was performed. The velocities directly output from the code were compared to the velocities computed by integrating the predicted accelerations, see Figures 13 and 14. The two velocity curves were nearly identical for Location **A** and are not included in the paper. For Location **B**, Figure 13, the variation is small but clearly identifiable. This discrepancy in the predicted velocities was later found to produce unacceptable scatter in the accelerations for symmetric locations. For Location **C**, Figure 14, the difference in predicted velocities is dramatic. Note that the velocity from the integrated acceleration shows a well-defined increase in the slope of the velocity at 0.03 s, which agrees with the large acceleration in Figure 12 at 0.03 s.

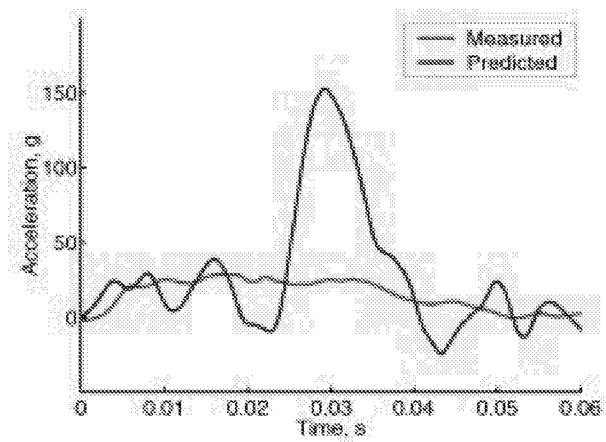

Figure 12. Comparison of measured and predicted accelerations at Location C.

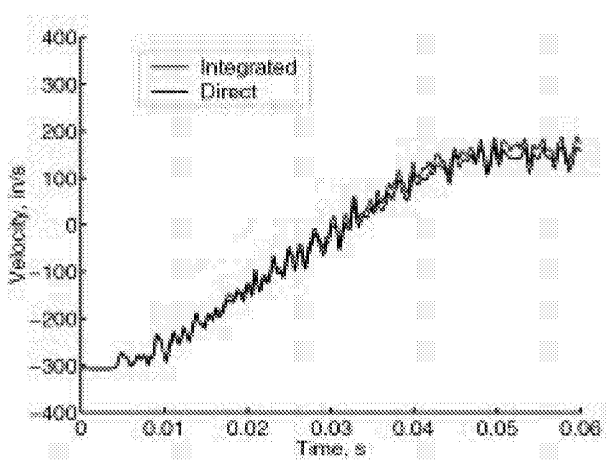

Figure 13. Comparison of predicted velocities directly output from code and computed by integrating the accelerations for Location B (Output sampled at 10 kHz).

These errors resulted from using an insufficient output sampling rate for the simulation results, similar to aliasing. The results at Location **C** were re-sampled at every time step. The resulting velocities are shown in Figure 15. Note that no difference between the two velocity computations is evident.

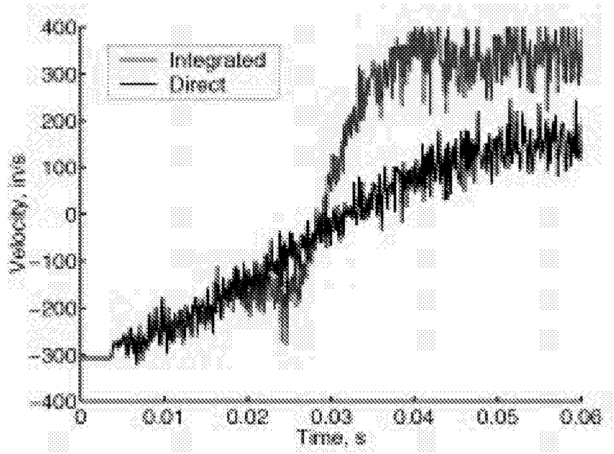

Figure 14. Comparison of predicted velocities directly output from code and computed by integrating the accelerations for Location C (Output sampled at 10 kHz).

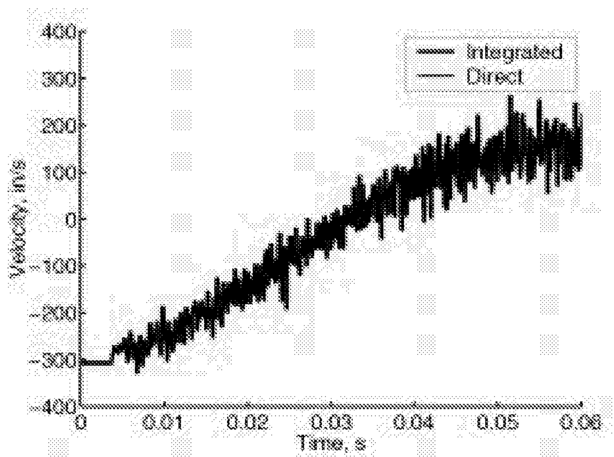

Figure 15. Comparison of predicted velocities directly output from code and computed by integrating the accelerations for Location C (Output sampled every step).

This problem has been addressed here to highlight the need to check the simulation sampling rate by comparing the velocities computed by integration of the predicted accelerations with the velocities directly predicted by the simulation code. Fortunately for this application, the time step is fairly uniform so that the filter coefficients were computed based on the average time step. No attempt was made to find the optimal sampling rate. **The discrepancy between the Integrated curves in Figures 14 and 15 is simply caused by insufficient sampling of the simulation results.** Insufficient sampling of the predicted results can cause the analyst to erroneously modify models to improve correlation.

The maximum accelerations for the positions shown in Figure 5 are shown in Figures 16 and 17, for the filtering frequency of 100 Hz and 24 Hz, respectively. Individual values are represented by symbols, while the mean is denoted by lines. The mean was based on averaging the four symmetric locations. In Figure 16, note the close correlation (less than 1 g) for the outboard positions, 01 — 04. The variation for the remaining locations varies from 1 g to 7g. When filtered at 24 Hz, the maximum accelerations show a clear delineation between measured and predicted values. The difference in the mean ranges from 4 to 6 g. These results clearly show that the correlation accuracy is dependent on the filtering frequencies. An unanticipated effect was that for 100 Hz the outboard predictions were closer than for 24 Hz.

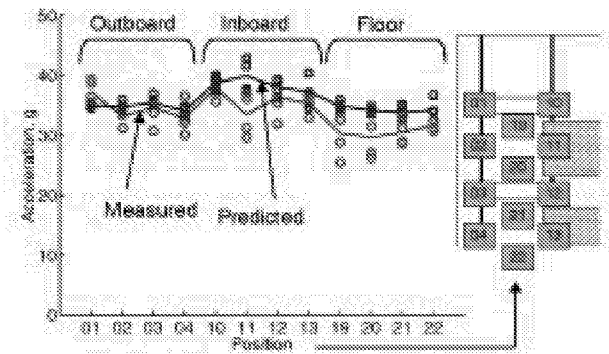

Figure 16. Comparison of measured and predicted maximum accelerations when filtered at 100 Hz.

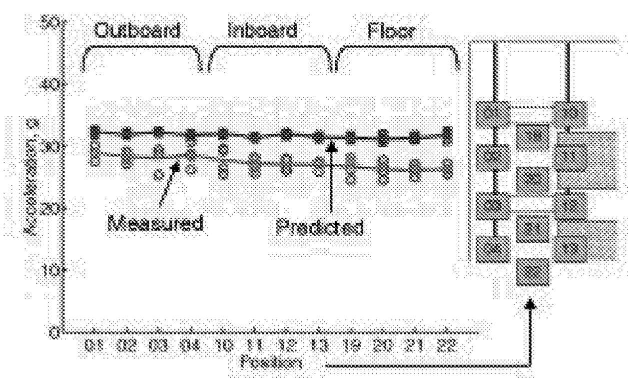

Figure 17. Comparison of measured and predicted maximum accelerations when filtered at 24 Hz.

Concluding Remarks

This paper described an activity to better quantify the accuracy of crash test and analysis correlation. The work in this paper concentrated on the test and simulation results for an advanced-concept, full-scale fuselage section. A drop test of the section was conducted to provide data for correlation with crash simulations. A detailed finite element model was developed for execution in MSC.Dytran to generate crash simulations. The results presented in this paper concentrated on the effect of several data reduction processes, to include filtering frequency and sampling rate, on the correlation accuracy.

In summary:

- Test structures should be instrumented not only for concept evaluation, but also for correlation with finite element simulation results.
- Insufficient sampling of the predicted results can produce aliasing errors in the accelerations. Aliasing can be readily identified by comparing the velocities directly predicted by the simulation code with the velocities computed by integrating the predicted accelerations.
- Clearly, the filtering frequency affects the correlation accuracy. Standards for selecting the filtering frequency need to be addressed.
- Symmetric transducer locations enable evaluation of data quality. For essentially symmetric positions, the scatter in acceleration time histories was relatively large, 40 %. A concern was raised as to how to appropriately quantify not only the correlation of test and analysis but also channel-to-channel variations.
- Various methods for evaluating the comparison of measured and predicted results were presented. These methods included the traditional filtered time histories as well as quantities derived from the time histories, such as the maximum acceleration. Such a presentation of several approaches can be valuable for evaluating global modeling accuracy as well as highlighting both the subtle and pronounced differences between test and analysis.

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