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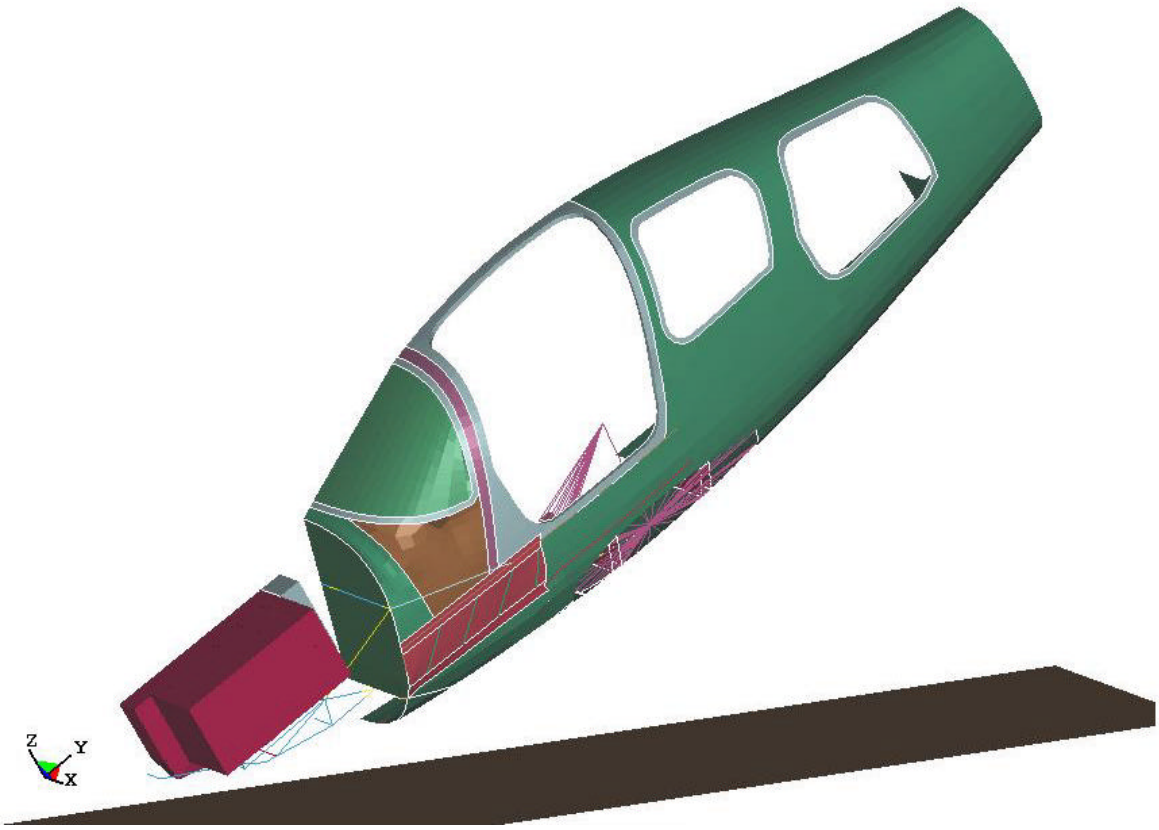
Design and Construction of a Crashworthy Composite Airframe



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Abstract

The goal to improve the crashworthiness of composite general aviation aircraft was identified at the inception of the AGATE program. The creators of the program recognized that accident mitigation is an important consideration that must be addressed in addition to accident avoidance if one is to provide the public with general aviation aircraft that are safe and that are perceived to be safe. The Integrated Design and Manufacturing Workpackage refined this goal by recognizing that the most effective way to enhance aircraft crashworthiness performance is to employ a systems approach in the design process. Their ensuing efforts included the design of modifications to the Lancair Columbia 300 airframe to mitigate very severe impact conditions. The design process utilized both linear and nonlinear finite element computer programs in static and dynamic analyses. A full-scale test article was subsequently fabricated and tested at the Impact Dynamics Test Facility at NASA Langley Research Center. This report provides detailed documentation of the fabrication process in addition to a description of the design process.

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Introduction

The public perception of General Aviation Safety was identified as an impediment to the successful marketing of AGATE aircraft to the so-called latent market. This market was defined as non-pilots whose travel needs could be effectively provided by AGATE aircraft [1]. While considerable guidance information is available in the literature regarding the crashworthy design of rotorcraft [2-7] and larger GA aircraft [8], only limited information is available for the design of small general aviation aircraft. The AGATE Advanced Crashworthiness Group (ACG) responded to this need by developing a Systems Approach to Crashworthiness for General Aviation Aircraft. Much of this work extended the efforts of Terry [9-10], who demonstrated the feasibility of designing a crashworthy general aviation aircraft. He conducted four full-scale drop tests of a composite general aviation aircraft at NASA's Impact Dynamics Test Facility, two onto a hard surface, and two into soft soil. The last two of these tests, one onto a hard surface and the other into soft soil, were both judged to be survivable. These results represent a significant improvement over those reported by Castle [11] following tests of earlier designs.

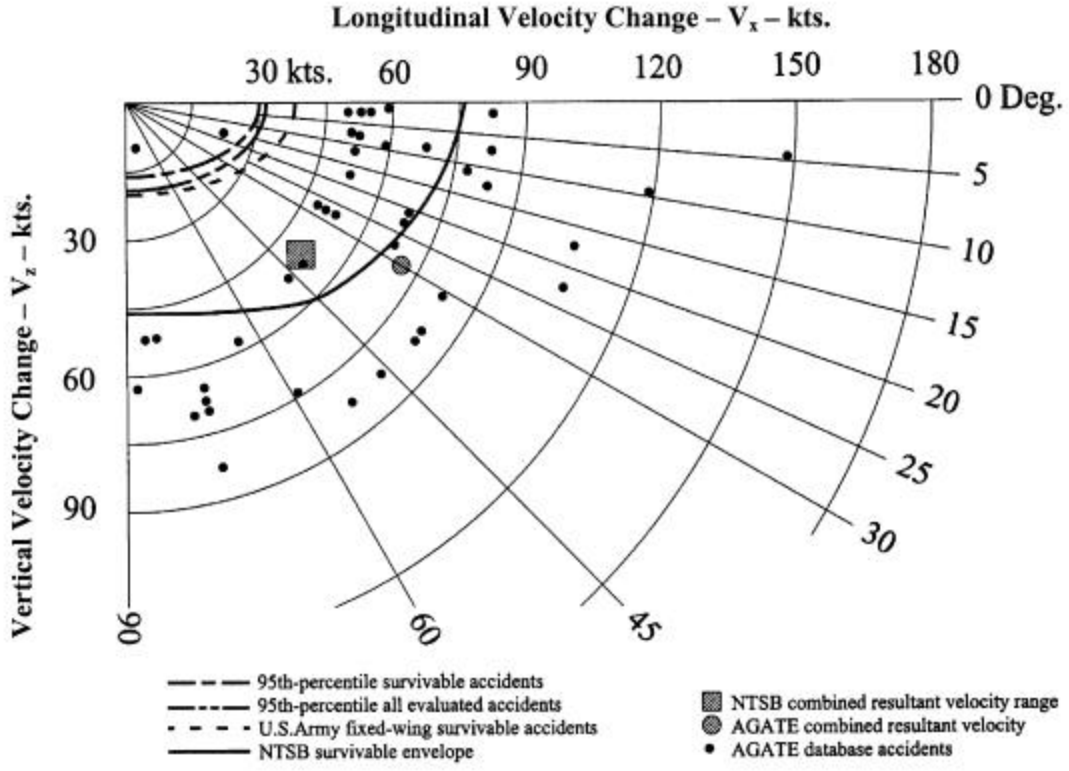

Fig. 1 – General Aviation Accident Data

The AGATE Advanced Crashworthiness Group developed the impact condition for this design by conducting their own accident investigation study [12]. A summary of these data are presented in Fig. 1. Each data point on this plot represents a survivable accident, which was defined as one in which there was at least one survivor and at least one fatality.

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Considering these data, the group subsequently defined the AGATE test condition as V_{so} (57 kts) at a 30º nose-down attitude as shown in Fig. 2 below. Note the flight path was also defined as 30º nose-down. This test condition was judged to be a very severe, but survivable impact and is presented along with survivable accident data in Fig. 1 above.

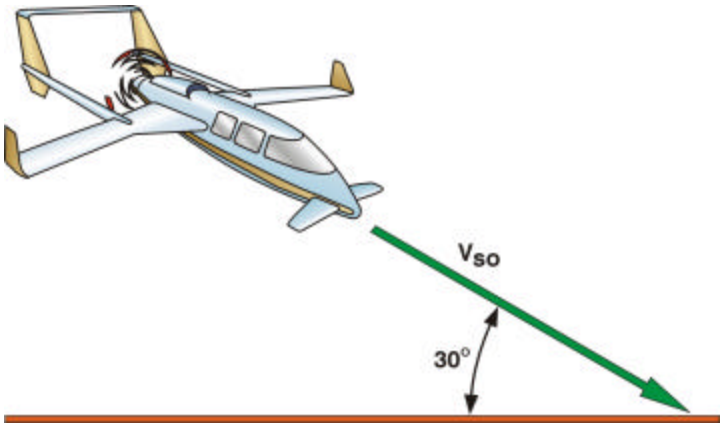

Fig. 2 – AGATE Test Condition

The AGATE group selected the Lancair 300 (Fig. 3) fuselage as the starting point for developing the drop test article with which to demonstrate the efficacy of the systems approach to crashworthiness. This report describes the methodology used to design the cabin structure of the drop test article.

Fig. 3 – Baseline Airframe

The fundamentals of crashworthiness design are reflected in the acronym *CREEP*, which stands for

- *Container*
- *Restraint*
- *Environment*
- *Energy management*
- *Post-crash factors*

The first of these, *Container*, reflects the need to maintain a survivable volume throughout the crash event. The second, *Restraints*, identifies the need to restrain the occupants within the vehicle without imposing injurious loads. *Environment* represents the need to prevent the occupants from injuring themselves by striking an object within their flail envelope. *Energy management* refers to the need to mitigate occupant loads and accelerations

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to noninjurious levels. This issue involves the entire structure in the load path between the points of the vehicle that contact the ground and the occupants. Finally, *Post-crash factors*, reflects the need to address threats posed by post-crash fires or water hazards. An important point to consider, when addressing post-crash hazards, is to provide for rapid egress from the vehicle after the accident.

The objectives of the airframe design are to size the structure so that a survivable volume is maintained throughout the impact response and to attenuate the seat-occupant-restraint system loads to survivable levels throughout the crash event. The AGATE design utilized existing FAA certified seats and restraint systems, which comply with the requirements of 14 CFR 23.562. This addressed the *Restraint* and *Environment* requirements as well as contributing to the *Energy Management* solution for the occupant kinetic energy. Thus the drop test article addresses the *Container*, *Restraint*, *Environment*, and *Energy Management* requirements in the crashworthy design.

The ACG was mindful of the cost impact of incorporating advanced crashworthiness capabilities in the AGATE aircraft from the beginning of the program. They therefore adopted a straightforward design methodology, which largely utilizes traditional linear-elastic analysis and design tools to define the airframe. This reduces the need to use more expensive (time consuming) nonlinear analyzers such as LS-DYNA [13] and MADYMO [14] to a manageable level. Consequently the cabin design effort utilized several linear and nonlinear finite element computer models. CSA/NASTRAN [15] was employed in the linear analyses and LS-DYNA was used to analyze the nonlinear models. Pre- and Post-Processing was supported by SDRC FEMAP [16] and MSC/PATRAN [17]. The analyses also employed classical lamination theory and traditional hand analysis using techniques described in References 18-21.

The firewall loads were estimated using a model of the crashworthy engine mount and a rigid airplane impacting a rigid surface. These were compared with loads estimated from Terry's drop test data for impacts into soft soil [9,10,22]. This model represented the engine/propeller and airframe inertia terms as two distinct mass elements. Loads for the more severe soft-soil impact condition were estimated by approximately doubling the values predicted for the hard surface case. This analysis produced a 50-G longitudinal load condition at the firewall. The loads predicted by this model were then used in the design of the forward fuselage structure. A traditional linear-elastic approach was employed in the design of these structural reinforcements using the CSA/NASTRAN computer program. The preliminary and final solutions were subsequently analyzed using the nonlinear LS-DYNA finite element program.

This report documents the process used to design the test article modifications as well as the final design. Detailed descriptions of the finite element models employed in this design effort are described as well.

Crashworthy Airframe Design

The AGATE Advanced Crashworthiness Group developed a conceptual design of an AGATE aircraft, which incorporated a number of occupant protection strategies to deal with both hard surface and soft soil impacts. These concepts are illustrated in Fig. 4.

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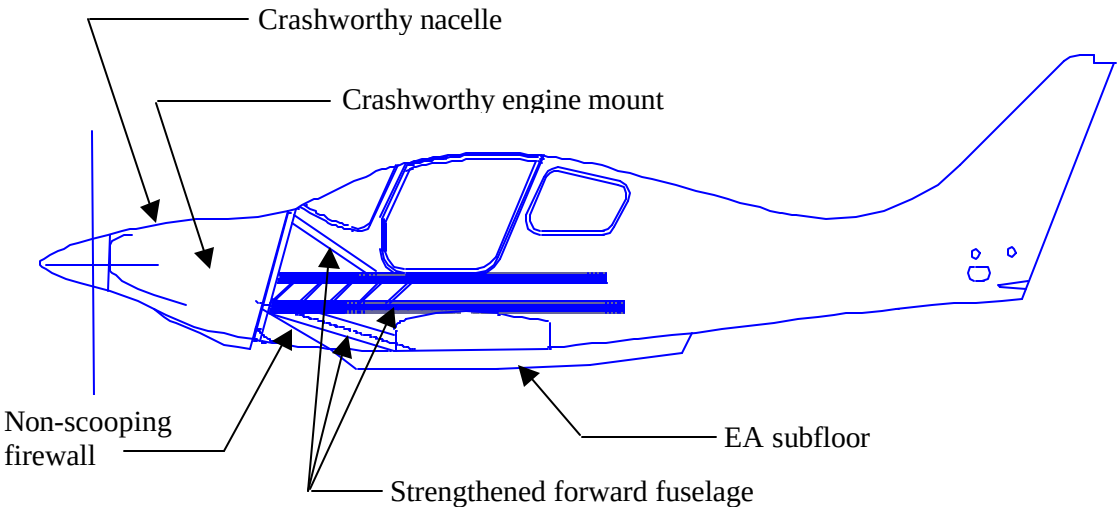

Fig. 4 – Crashworthy Features of the AGATE Aircraft

The first of these is a crashworthy cowl and engine mount. These features, in combination with the ramp at the juncture of the firewall and belly skin are intended to provide nose-up pitch acceleration during soft soil impacts. This acceleration will enable the fuselage to "ride-up" on the soil, thus prolonging its slide out. Terry's results also identified the importance of designing the cowl and engine mount as a system for the purpose of producing this response. The results of the Terry SBIR project demonstrated that the slide-out distance of an aircraft with these design features is nearly double that of earlier designs which generally come to rest in the bottom of the impact crater [9]. Design features that extend the slide out distance are highly desirable since, in view of classical impulse-momentum theory, anything that doubles the time required to bring the body to rest halves the average accelerations experienced by the occupants. Lowering occupant inertia loads is obviously desirable since this serves to mitigate head injuries and thoracic trauma. Appendix A provides a drawing of the crashworthy cowl design used in this test. Appendix B provides some pictures of a math model of the engine mount designed for this drop test. Fig. 5 shows a picture of the non-scooping firewall on the drop test article.

Fig. 5 – Crashworthy Features of the AGATE Aircraft – Non-scooping Firewall

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The next occupant protection strategy involves the provision of an occupant compartment that is sufficiently strong to withstand a severe impact event. This requires that the occupant compartment retains its volume and where damage occurs, it must occur in a manner that is not potentially injurious to the occupants. Thus the strength of all of the structure surrounding the occupants must be evaluated. Examples of specific structures include the firewall, floor, sidewalls, and overhead fuselage. Fig. 6 shows some of the actual structural modifications from the interior of the fuselage.

Fig. 6 – Crashworthy Features of the AGATE Aircraft – Strengthened Occupant Compartment

The need also exists to attenuate the lumbar loads (vertical accelerations) experienced by the occupants in order to avoid back injuries. The solution to this problem is challenging since aircraft stability and control, and structural requirements frequently lead to designs where the front wing spar is positioned directly below the crew seats in low-wing general aviation designs. This arrangement significantly reduces the stroking distance available to the seat designer and thus contributes to the difficulty of effectively providing spinal protection. The AGATE design team addressed this by specifying the use of an energy absorbing subfloor located below the lower spar caps.

The energy absorbing subfloor structure was configured as two semi-cylinders that extended from the exhaust lobes at the aft edge of the cowling (Fig. 7) to the aft edge of the baggage compartment. Rigid foam was installed in these cylinders under the front and rear spars and under the baggage compartment. The purpose of this system is to mitigate the vertical accelerations at the seat tracks and specifically to deal with the tail slap-down phenomena identified by Terry [9]. The pitch accelerations that are produced during the initial impact lead produce a second impact where the tail contacts the ground. Terry's results indicate that this produces nearly the same vertical accelerations for the rear-seat occupants as those experienced by the front-seat occupants. The conceptual design provided for the attenuation of these loads by locating energy absorbing elements (rigid foam) under these locations.

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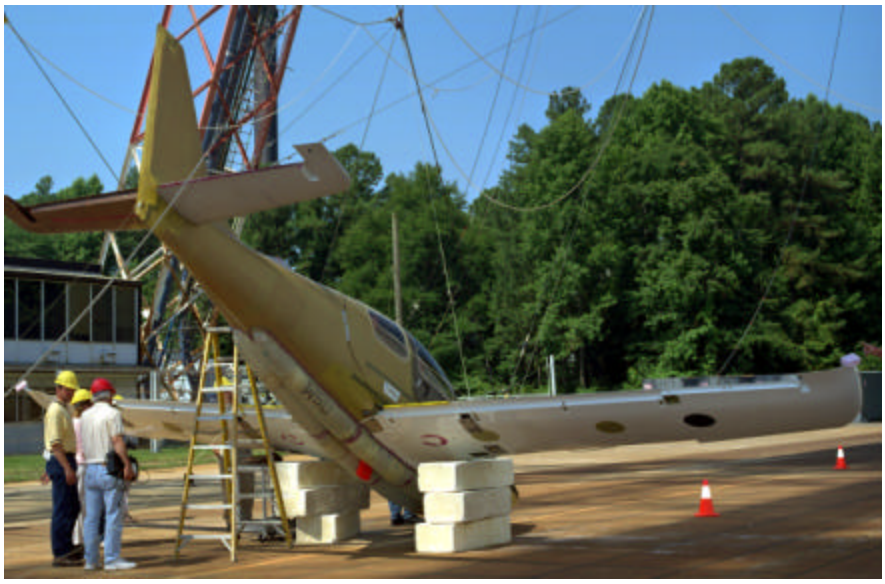

Fig. 7 – Crashworthy Features of the AGATE Aircraft – Energy Absorbing Subfloor

Ideally, the design process represents a Systems Approach to Crashworthiness, illustrated in Fig. 8 below, which considers the interactions between the various elements of the system. During this design effort, the primary interactions considered were between the engine mount, crashworthy cabin, and the energy absorbing subfloor.

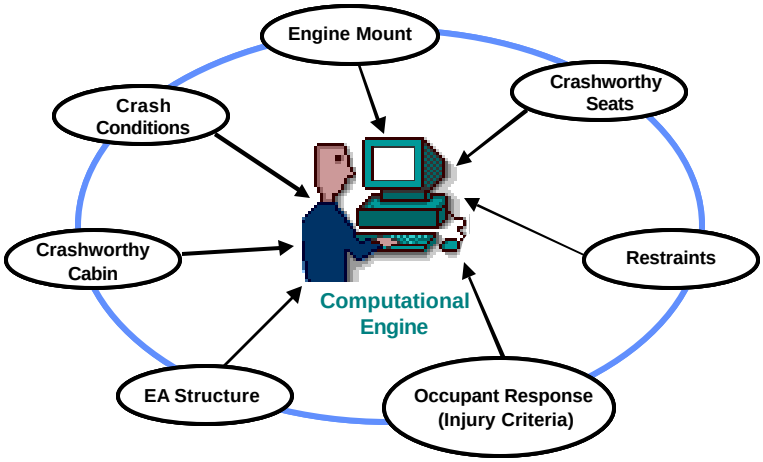

Fig. 8 – Systems Approach to Crashworthiness

The design process for a crashworthy vehicle necessarily starts with the specific structure that first comes into contact with the ground and proceeds along the load path from that point to the vehicle's center of gravity. This approach is consistent with the computation of transient solutions using computer programs such as LS-DYNA or MADYMO since they also force one to start the design process at this same point and follow the same path. Thus for this case, the design process started with consideration of how to best define the engine mount and lower cowl. It then progressed to consideration of the forward fuselage and finally consideration of the energy absorbing subfloor. Since the envisioned test will produce baseline data for a crashworthy design, it will be conducted using seats and restraints that have been designed and certified to the dynamic seat test requirements

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specified in 14 CFR 23.562. While the performance of these safety technologies wasn't modeled as a part of the design process, their performance will be evaluated in the subsequent drop test.

Recall that the Lancair Columbia 300 airframe served as the starting point for the test article design. This structure is a sandwich design consisting of fiberglass face sheets that are bonded to a Nomex honeycomb with core thicknesses of 1/4-in., 3/8-in. and 1/2-in. The face sheets are layed-up using Newport NB321/7781-1 E-Glass cloth. Two graphite longerons are installed in the fuselage sidewalls of the production aircraft at approximately WL 99 and 94.6. The fuselage also contains graphite stiffeners in the frames, located forward and aft of the cabin doors.

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Detailed Design

The crashworthy design process begins with the cowl and the engine mount since they are the first structural elements to contact the ground. The airframe modifications were designed for a 30° nose-down impact condition into soft soil. A subsequent stress analysis of this structure was then performed for the hard-surface test condition. The primary function of the cowl in a crashworthy design is to prevent the aircraft from scooping soil during a soft soil impact. Since this is a hard surface impact, it is not necessary to consider the cowl performance for this test.

The engine mount design was supplied by Simula Technologies, Inc. Simula also provided a finite element model that was used in subsequent design and analysis efforts. In addition Simula shared their MSC/DYTRAN model of the entire airframe, which they constructed from an MSC/NASTRAN model obtained from Lancair. Portions of this MSC/DYTRAN model were utilized in creating an LS-DYNA finite element model. This is one of three different models that will be described at different stages of this document. The analysis and design process started with the simplest possible model, which consisted of an LS-DYNA finite element model of the firewall, engine mount, engine, and a rigid body representation of the remainder of the airframe. It was used to predict the firewall loads at the firewall-engine mount interface. Fig. 9 shows this model impacting a rigid surface. This model is illustrated in Fig. 10, without the engine, to better illustrate the engine mount itself.

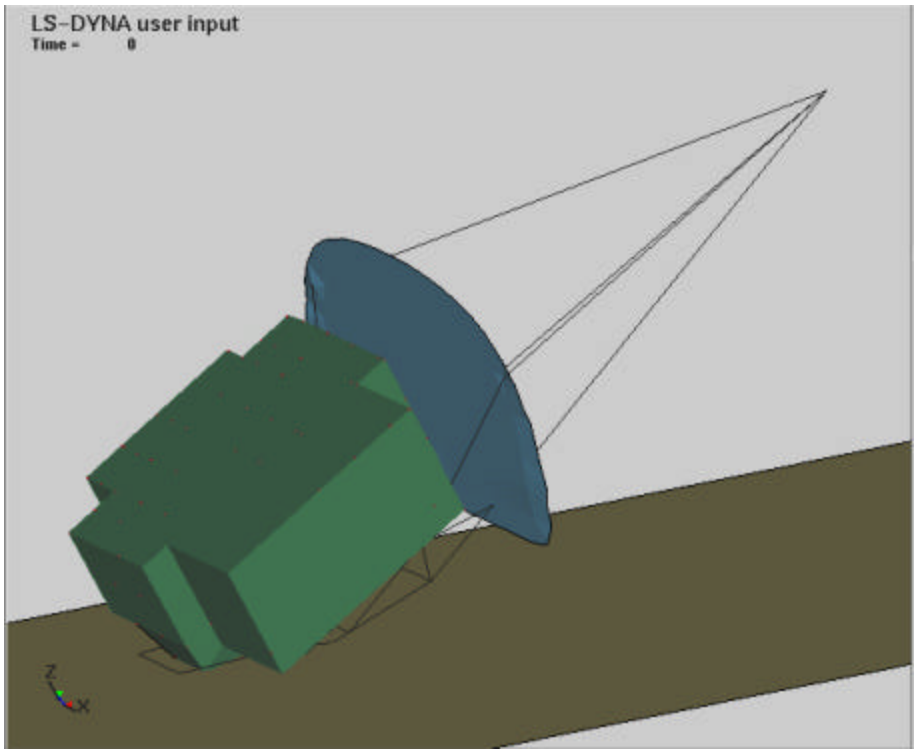

Fig. 9 – LS-DYNA Model of Simplified Airframe

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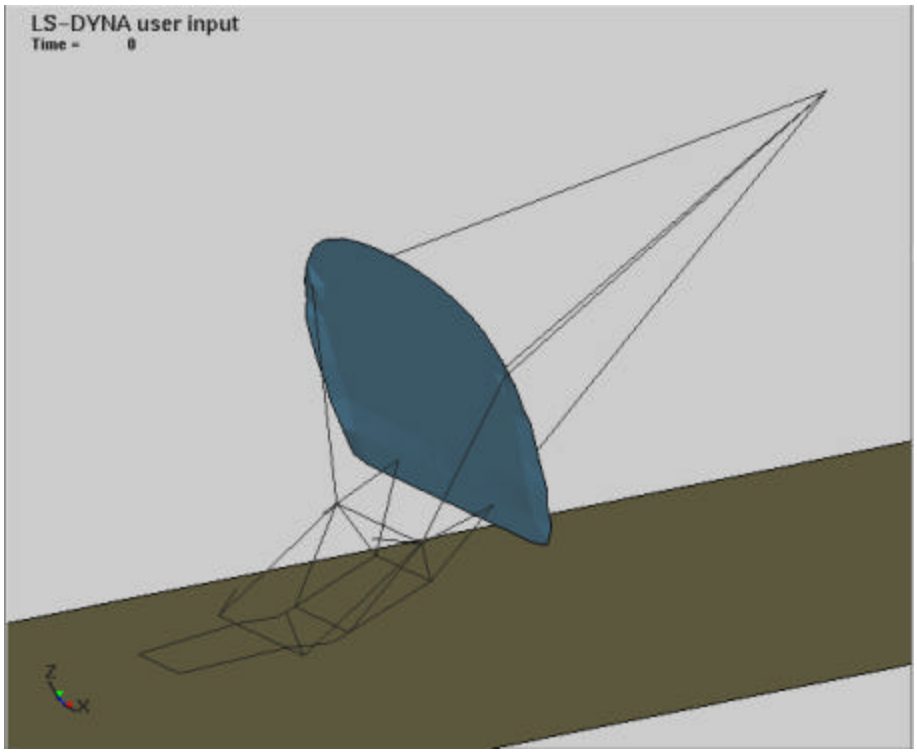

Fig. 10 – LS-DYNA Model of Simplified Airframe (without engine)

Note that the coordinate system used for all of these models specifies x as the lateral direction (+ port), y as the longitudinal direction (+ aft), and z as the vertical direction (+ up) for the aircraft. The authors recognize that this is not a commonly used aircraft coordinate system, however the effort required to modify the model to comply with the standard convention was not judged to be value-added.

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Beam elements with nonlinear material properties were used to represent the individual members in the engine mount model, shown in Fig. 11. Beam elements were used to model the individual engine mount members with the exception of the discrete energy absorbers. The 4130 steel was represented as an elastic-plastic material with a yield strength of 75,000 lb/in^2. The reader should note that the yield strength of steel is known to exhibit significant rate sensitivity and thus some uncertainty exists with respect to this strength value. The upper two members of the engine mount were designed as discrete energy absorbers with the nonlinear load deflection curve presented in Fig. 12.

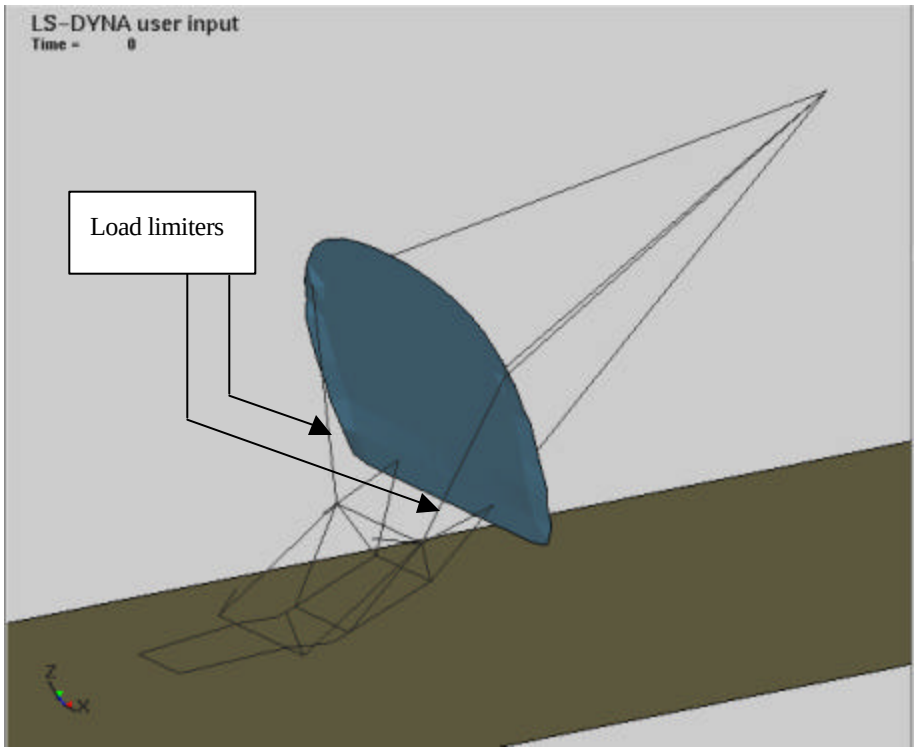

Fig. 11 – Load Limiting Engine Mount Members

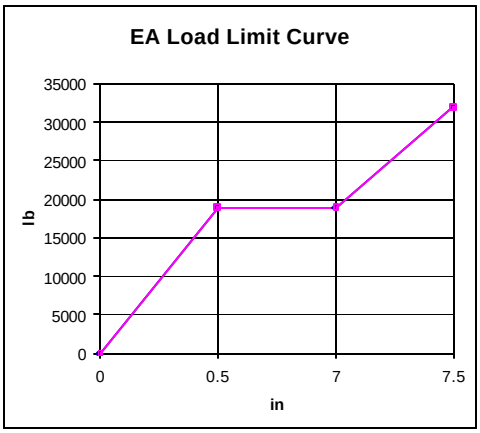

Fig. 12 – Load-Deflection Curve used for Load Limiting Members

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The engine/propeller and airframe mass elements used in this model are associated with nodes 523 and 249, respectively. The mass and center of gravity locations of these elements are shown in Fig. 13. The corresponding data is presented in Table 1 and the inertia properties are presented in Table 2 below.

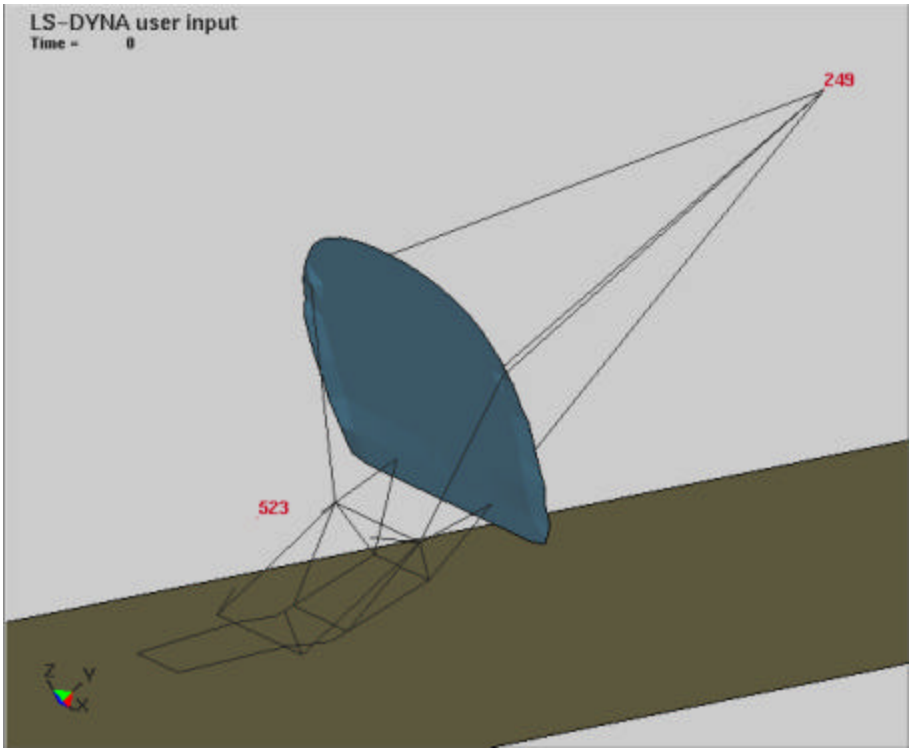

Fig. 13 – Engine/Propeller and Airframe Mass Elements

Table 1 – Mass Properties of Rigid Airframe Model

Description	Wt (lb)	x (in)	y (in)	z (in)
Engine/Propeller	400	0	41.1	101.1
Airframe	2800	0	124	93

Table 2 – Inertia Properties of Rigid Airframe Model

Description	Ixx ($lb\text{-}in^2$)	Iyy ($lb\text{-}in^2$)	Izz ($lb\text{-}in^2$)	Ixy ($lb\text{-}in^2$)	Iyz ($lb\text{-}in^2$)	Izx ($lb\text{-}in^2$)
Engine/Propeller	183.0	1.0	1.0	0.0	0.0	0.0
Airframe	16000.0	21100.0	42900.0	0.0	0.0	0.0

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The engine mount was fabricated from 1.0-in. O.D. 4130 steel tubes with a wall thickness of 0.049 in. The section properties of these members are summarized in Table 3.

Table 3 – Section Properties of Engine Mount Tubes

Description	**A** (in^2)	**Ixx, Iyy** (in^4)	**J** (in^4)
1.0 in. x 0.049 in. steel tube	0.1464	0.016594	0.033183

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An analysis was made that simulated the impact of this simple model into a hard surface at an impact angle of 30°, and an impact speed of 94.5 ft/sec = 57 knots. The contact model considered a static coefficient of friction of 0.4 and a dynamic coefficient of friction of 0.3. As a point of reference, steel on steel is estimated to have a static coefficient of friction of 0.8 and a dynamic coefficient of friction of 0.4. The results of this analysis are illustrated by the time sequence presented in Fig. 14.

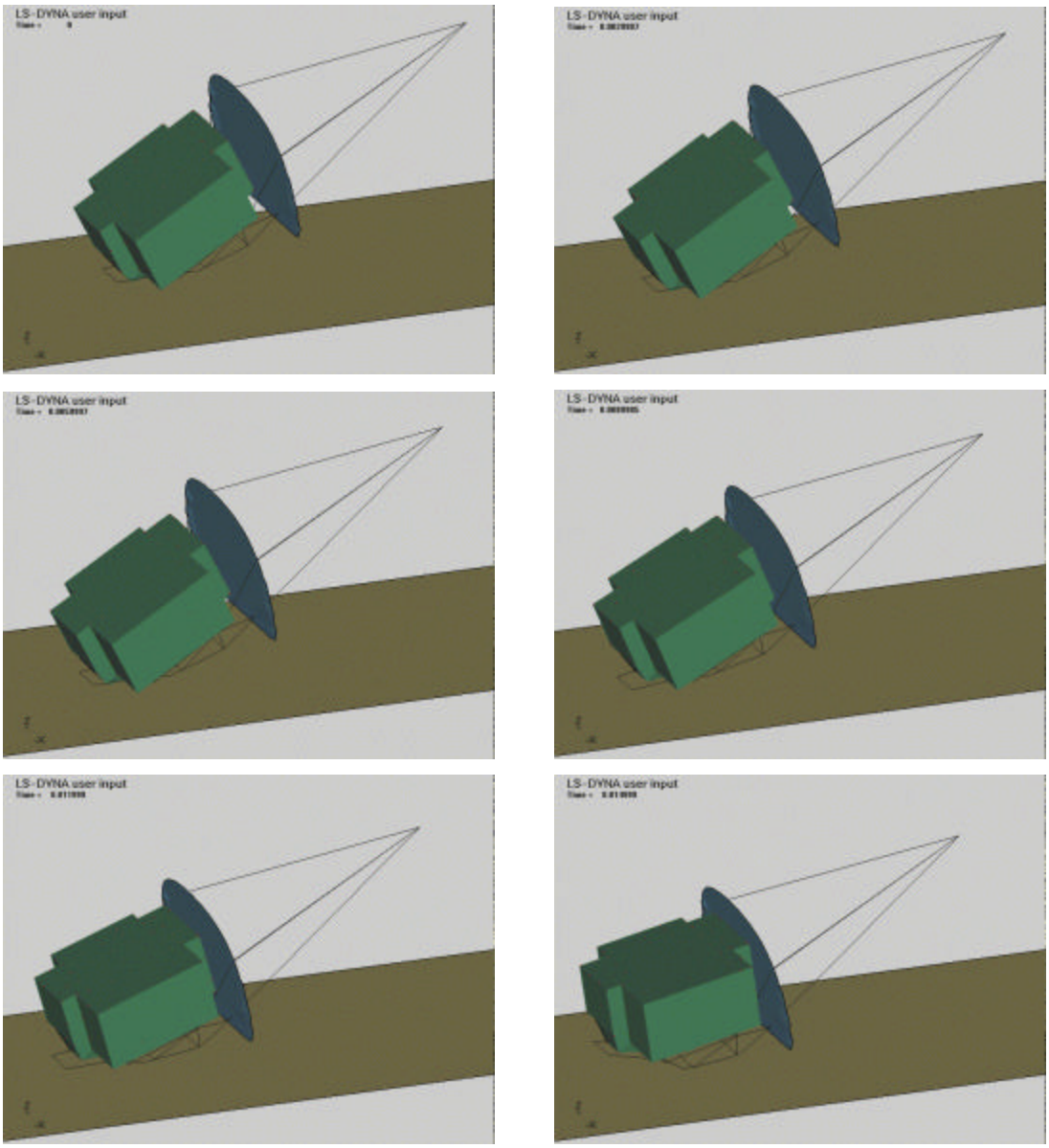

Fig. 14 – LS-DYNA Analysis Time Sequence

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The firewall loads were predicted using the engine mount model shown in Fig. 15. The elements of specific interest are labeled in this figure.

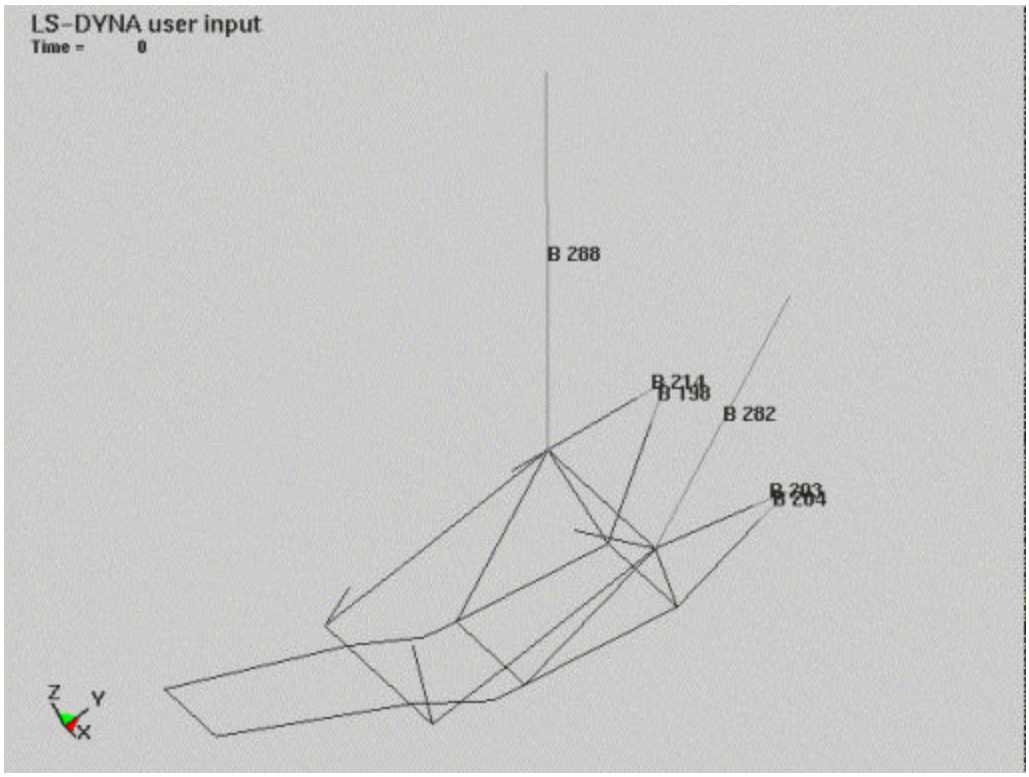

Fig. 15 – Engine Mount Attachment Beams

The time histories of the engine mount forces on the firewall are presented in Figs. 16-18. The maximum force at each of the upper engine mounts is predicted at time t = 0.008 sec, with a magnitude of 19,000 lb (see Fig. 16). The upper left hand engine mount force acts along the unit vector $\mathbf{u}_1$ = [0.479,0.581,0.658]. The force at the lower engine mounts is predicted in two different members. In each upper member of the lower engine mount, the maximum force is at time t = 0.075 with a magnitude of 11,000 lb (see Fig. 17). This force acts along the unit vector $\mathbf{u}_2$ = [0.117,0.975,-0.190]. The maximum force of 11,000 lb (see Fig. 18) is predicted to be developed in each lower member of the lower engine mount at time t = 0.075. This force acts along the unit vector $\mathbf{u}_3$ = [0.387,0.830,0.403]. Note that all of these unit vectors are defined in the aircraft's global coordinate system, which is illustrated in Fig. 15.

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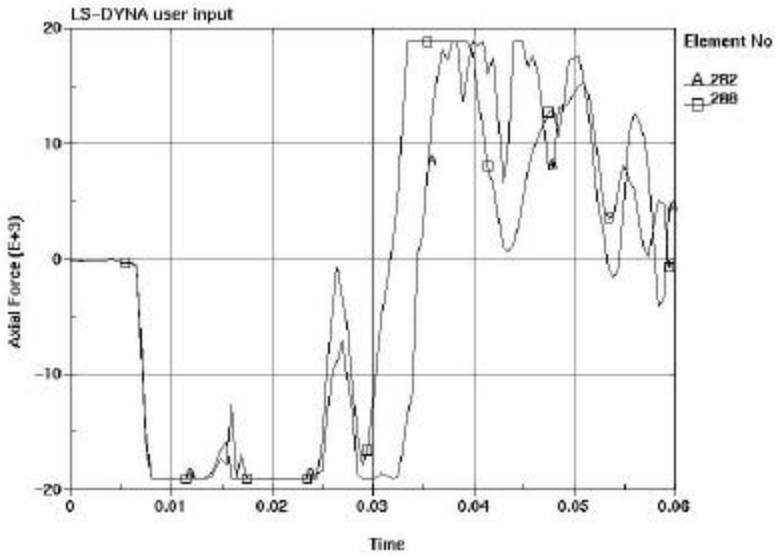

Fig. 16 – Force-Time History for Upper Engine Mount Elements

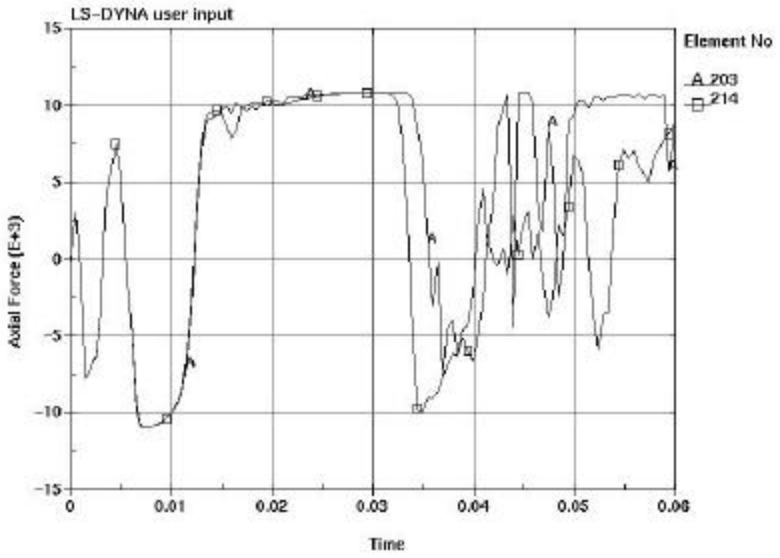

Fig. 17 – Force-Time History for Lower Engine Mount Elements (Upper Set)

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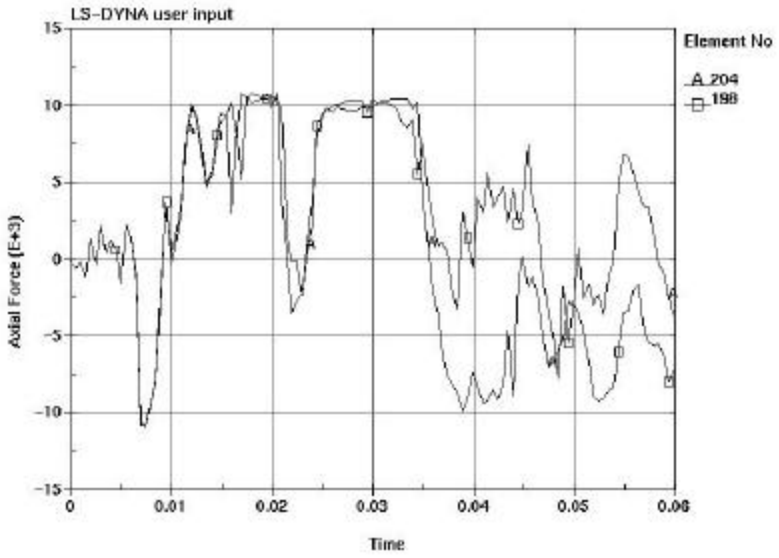

Fig. 18 – Force-Time History for Lower Engine Mount Elements (Lower Set)

These predicted loads were utilized to calculate longitudinal loads at the upper and lower engine mount locations. It is noted that a resultant load factor of 21 G's was measured during Terry's "Test 3" for an impact into soft soil, which is comparable to that predicted here [22]. The discrepancy between the values predicted for the soft-soil impact and those extracted from Terry's drop test data may be attributed to the uncertainties associated with the friction model, i.e., selecting a coefficient of friction and the accuracy of the contact force predictions. The resolution of these questions is complicated by the problematic nature of extracting load values from accelerometer data.

Since the strength of the forward fuselage is critical to success in maintaining a survivable volume, engineering judgment was used to establish a safety factor of 2. Thus the airframe loads for a soft-soil impact were assumed to be approximately twice those predicted by this model, or 50 G's. In addition, the results of the LS-DYNA analysis indicated a possible problem where the engine mount response causes the engine to penetrate the firewall and enter the cabin. This would be undesirable, as it would compromise the survivable volume.

The forward fuselage was also considered to be one of the most important portions of the cabin structure since it serves to transfer the engine mount loads from the firewall to the wing carry-thru structure, which is near the aircraft's c.g. This fiberglass sandwich structure was originally sized to resist flight and maneuver loads, not a 50-G impact load. Therefore, as in the case of the Terry program [9,10], this portion of the fuselage required significant reinforcement.

The structural reinforcement consisted of reinforcements for the two fuselage longerons and the shear web between them. It also included installation of two floor-level columns running between the lower engine mount locations and the front wing spar, as well as diagonal stringers between the upper engine mounts and upper longerons. The fundamental premise behind this design was that a survivable volume would be maintained if the forward fuselage structure didn't collapse. Thus, in this design, the windshield, doorframes, upper fuselage, and floor strengths were not considered to significantly contribute to maintaining a survivable volume throughout the crash event.

The detailed design concept employed herein should not be construed as a recommended design concept. Rather the intent of this effort was to demonstrate the use of a rational loads analysis for estimating the impact loads and a traditional structural design process that is appropriate for sizing the aircraft cabin. Surprisingly, this methodology isn't all that different from the methods commonly used to design structures for flight and maneuver loads.

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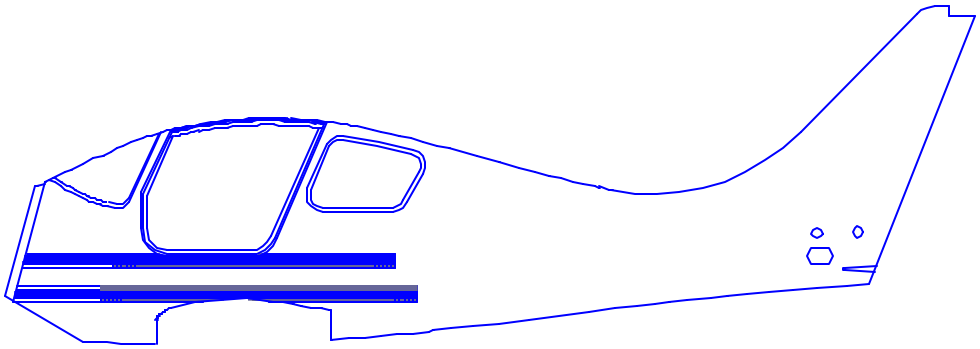

Fig. 19 – Baseline Fuselage Structure

The reinforcements for the forward fuselage structure (Fig. 19) were sized by first predicting the buckling strengths using the NASTRAN structural analysis model shown in Fig. 20 below. This model represented the fuselage structure between the firewall and the front door post. The bottom of this model is located at the lower longeron and the top is generally located at a waterline corresponding to the bottom of the windshield. The model also contained geometric imperfections that were arbitrarily imposed in the process of remeshing the geometry to model the diagonal shear web stiffeners. Geometric imperfections are routinely seeded in nonlinear finite element models [23]. There use here is consistent with the intent of these applications since it reduces the likelihood that the model will over-predict the buckling strength of the structure (see. Chapter 6.5.3 of Ref. 24).

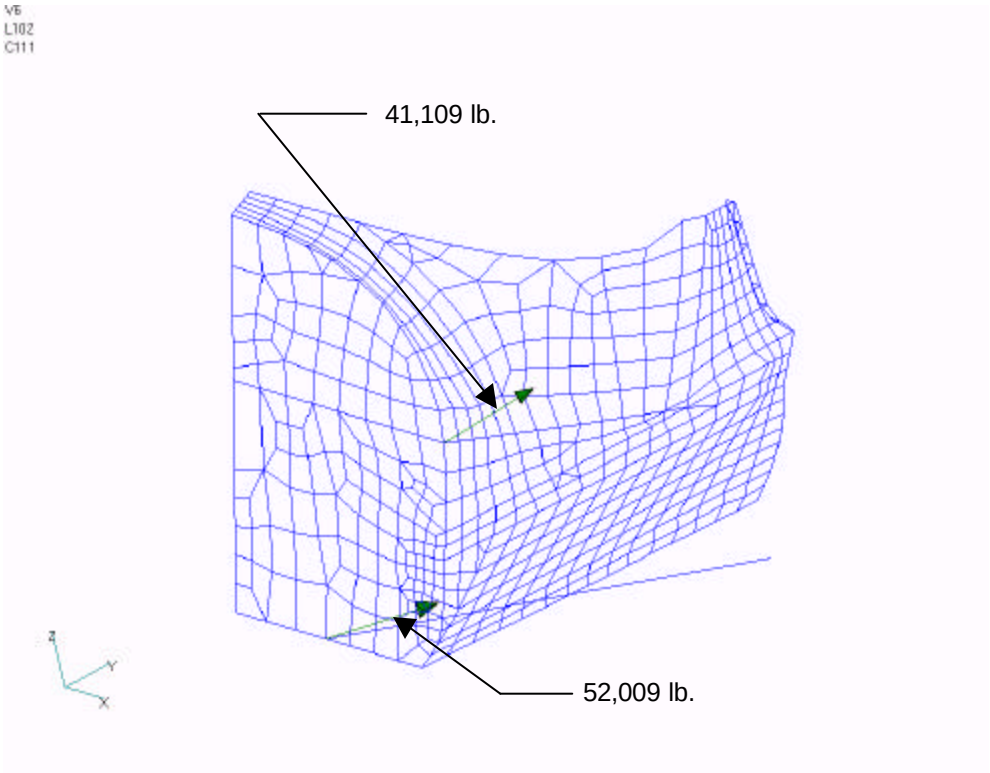

Fig. 20 – NASTRAN Model Showing Applied Loads

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The fuselage model was cantilevered from its aft end, i.e. all of the displacement and rotation degrees of freedom were constrained on this edge. These constraints will produce the following effects in the solution. By fixing these degrees of freedom, the finite element model is not able to redistribute the internal loads in the same way that the continuous structure does. Thus this clamped boundary condition will produce an "end effect" that is an artifact of the model and is not representative of the actual structural performance. In a similar manner, the end of the front window post was not constrained. Since the model implicitly "cut" this member, it underrepresented the stiffness of this structure and will subsequently predict greater deflections and lower buckling loads than provided by the actual structure. The engine mount column, running from the lower firewall, aft along the floor line, was pinned at both ends.

Finally, this model employed symmetry boundary conditions, to cut the size of the model in half. The symmetry boundary conditions, imposed on the centerline of the model, prevent lateral translations, as well as roll and yaw rotations.

The model supported the design of the structural reinforcements, shown in the Fig. 21. The diagonal shear web stiffeners were sized to produce a shear resistant beam. A gap was intentionally left between the ends of these stiffeners and the longerons. This lack of connectivity contributes to the conservatism of the model since it represents less strength than is probably generated by the structure. The upper diagonal stiffener was added to the structure to provide a load path from the upper engine mount to the upper longeron. The shear web stiffeners were oriented so that these members are loaded in compression during the initial impact loads. The -45º plies represent an effective structure to resist the diagonal tension loads that are simultaneously developed in the shear web. The reinforcements in the plane of the firewall were added to provide the necessary strength and stiffness to this member.

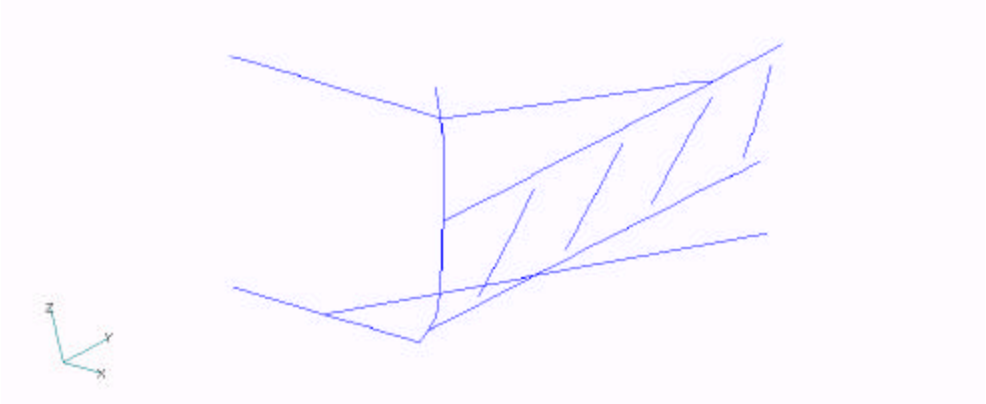

Fig. 21 – Fuselage Stiffeners

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The section properties of the stiffeners are defined in terms of AE_{REF}, $E_{REF}\,I_{yy}$, and $E_{REF}\,I_{ZZ}$. These properties are summarized in Table 4 below. The reference modulus, E_{REF} and Poisson's ratio were defined as 16.0E+06 psi and 0.321, respectively. The complete NASTRAN bulk data deck is included in Appendix C of this report.

Table 4 – Stiffener Section Properties

Description	PID	A – in^2	Iyy – in^4	Izz – in^4
Engine Mount Column *	1119	0.63024	0.46076	0.46076
Firewall / Fuselage Intersection (CROD)	1120	0.16		
Upper Longeron	1123	0.555	0.3623	0.1283
Lower Longeron	1124	0.555	0.45791	0.10836
Engine Mount Diagonal	1125	0.380	0.14405	0.027514
Shear Web	1126	0.2928	0.15995	0.044816
Upper Firewall	1127	0.3872	0.23045	0.06
Lower Firewall	1128	0.3744	0.08582	0.08582

* E_{REF} = 29.0E+06, ν = 0.32

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The laminate definitions for different portions of the forward fuselage NASTRAN model (Fig. 20) are summarized in Table 5.

Table 5 – Laminate Definitions

PCOMP 1111: Fuselage laminate H [45/0_6/45/0/45/0_4/45]						
	MID	**t - in**	**q - degrees**	**MID**	**t - in**	**q - degrees**
	101	0.0098	45.0	101	0.0588	0.0
	101	0.0098	45.0	104	0. 25	0.0
	101	0.0098	45.0	101	0.0392	0.0
	101	0.0098	45.0			
PCOMP 1112: Fuselage laminate L [45/0_6/0/0_4/45]						
	MID	**t - in**	**q - degrees**	**MID**	**t - in**	**q - degrees**
	101	0.0098	45.0	101	0.0588	0.0
	104	0.25	0.0	101	0.0392	0.0
	101	0.0098	45.0			
PCOMP 1113: Graphite Stringer [45/0_3/45/0/3_3/0_6/45]						
	MID	**t - in**	**q - degrees**	**MID**	**t - in**	**q - degrees**
	101	0.0098	45.0	101	0.0294	0.0
	102	0.12	0.0	101	0.0294	0.0
	101	0.0294	45.0	101	0.0588	0.0
	101	0.0098	45.0			
PCOMP 1116: Gusset [45/0/45/0/45/0/45]						
	MID	**t - in**	**q - degrees**	**MID**	**t - in**	**q - degrees**
	103	0.0104	45.0	103	0.0104	0.0
	103	0.0104	45.0	104	0.375	0.0
	103	0.0104	45.0	103	0.0104	0.0
	103	0.0104	45.0			
PCOMP 1117: Firewall [45/0_4/0/0_4/45]						
	101	0.0098	45.0	101	0.0392	0.0
	104	0.25	0.0	101	0.0392	0.0
	101	0.0098	45.0			

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Table 5 – Laminate Definitions (continued)

PCOMP 1122: Fuselage Shear Web [45/0_6/45/0/45/0_4/45]						
	101	0.0098	45.0	101	0.0588	0.0
	101	0.0098	45.0	104	0.25	0.0
	101	0.0098	45.0	101	0.0392	0.0
	101	0.0098	45.0			
PCOMP 11101: A-Pillar, m1 [45/0_9/45]						
	1	0.0098	45.0	1	0.0098	0.0
	1	0.0098	0.0	1	0.0098	0.0
	1	0.0098	0.0	4	0.25	0.0
	1	0.0098	0.0	1	0.0098	0.0
	1	0.0098	0.0	1	0.0098	0.0
	1	0.0098	45.0			
PCOMP 15001: A-Pillar, m2 [45/0_6/45/0/45/0_6/45]						
	1	0.0098	45.0	1	0.0098	0.0
	1	0.0098	0.0	1	0.0098	0.0
	1	0.0098	0.0	1	0.0098	0.0
	1	0.0098	0.0	1	0.0098	45.0
	4	0.25	0.0	1	0.0098	45.0
	1	0.0098	0.0	1	0.0098	0.0
	1	0.0098	0.0	1	0.0098	0.0
	1	0.0098	0.0	1	0.0098	0.0
	1	0.0098	45.0			

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The static solution for the 50-G unit load case is shown in Fig. 22 below. This load is hereafter referred to as *P**. Note that the elements representing the firewall were intentionally omitted from these figures to enhance their clarity.

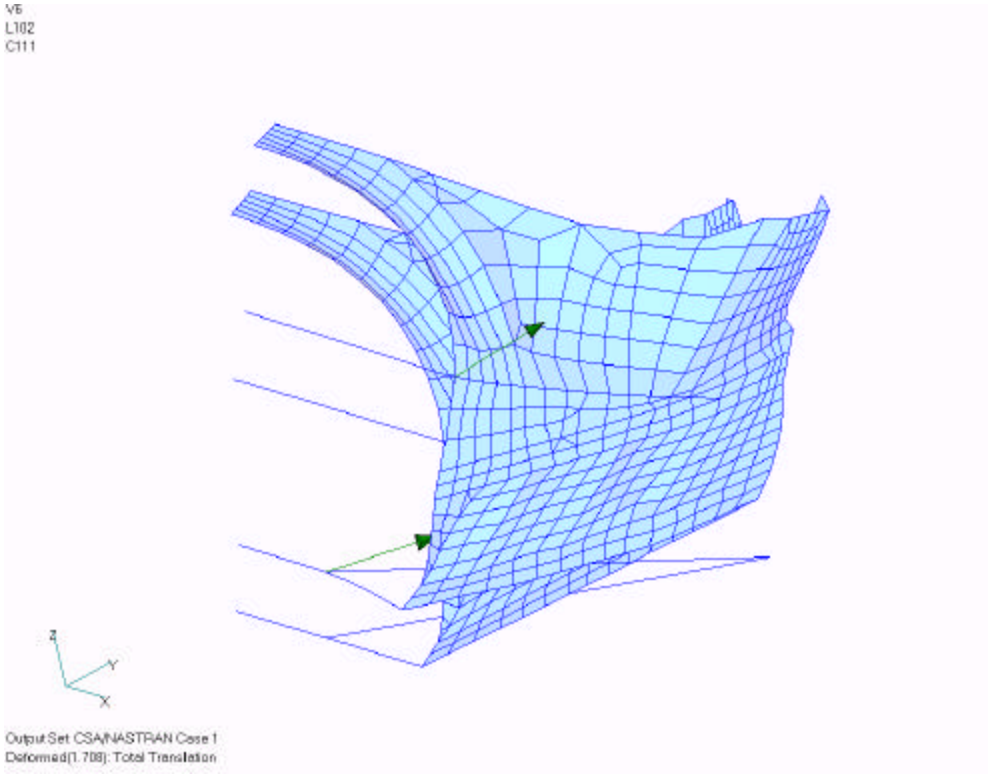

Fig. 22 – Static Displacement for the 50-G Crash Load Condition

The buckling loads were predicted for this model using the loads presented in Fig. 20 as the unit load case, *P**. The buckling load P_{cr} is computed as

$$P_{cr} = \lambda P^* \qquad (1)$$

where λ represents the eigenvalue.

An iterative process was employed to develop this design, which started with an initial "guess" for the geometry of each of the reinforcement stiffeners. The buckling loads were than calculated using a model containing the corresponding section properties. In this analysis, eigenvalues were extracted for the range of $-1.2 < \lambda < 1.2$, where positive eigenvalues represent the instability loads for the specified impact load condition. Negative eigenvalues indicate critical loads acting in a direction opposite to that shown in Fig. 20. As such, the latter represent some crude estimate of whether the forward fuselage structure is sufficiently strong to react to the nose-up pitch acceleration produced by the initial impact, which generates a download on the firewall. The reader is reminded that the initial impact will likely produce significant damage to the structure that is likely to have a significant effect on the structural response to the nose-up pitching accelerations.

These results were analyzed during each iteration of the design process, the section property definitions modified and the procedure repeated, until the smallest positive eigenvalue, for any mode involving the primary structure, was greater than 1. Eigenvalues that are less than 1 indicate that the structural strength is less than the imposed loads. The final results after completing five iterations of this process are presented below.

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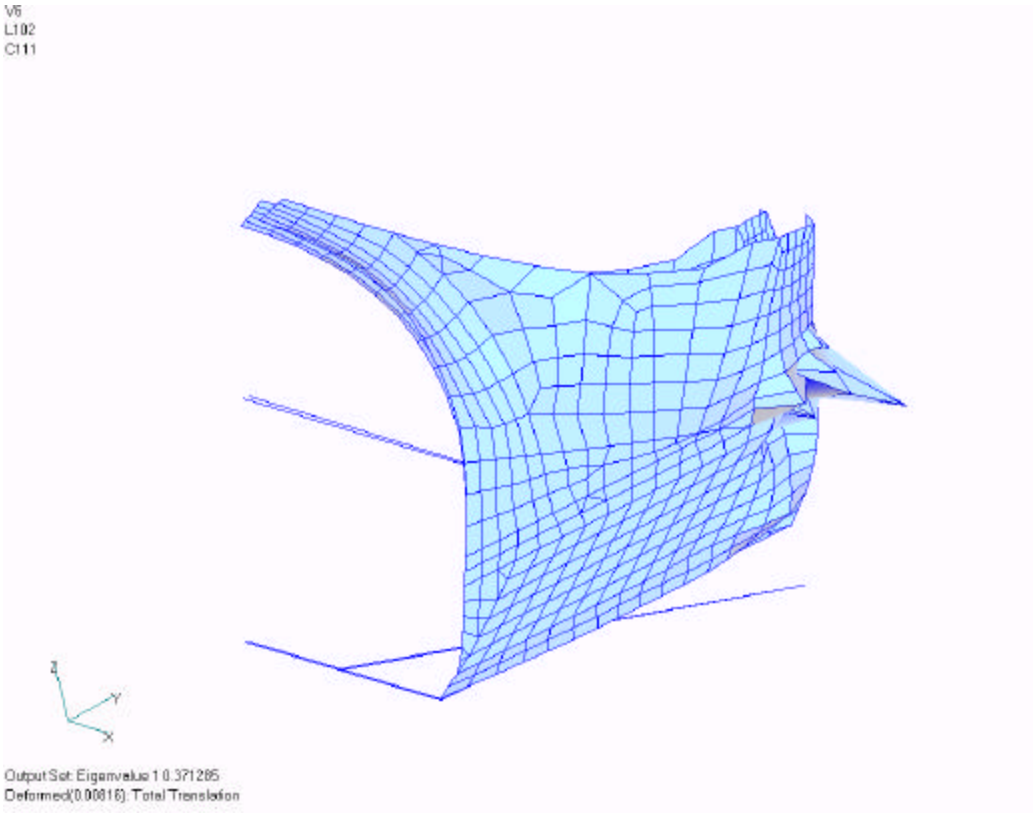

Fig. 23 – Mode 1, λ = 0.371285

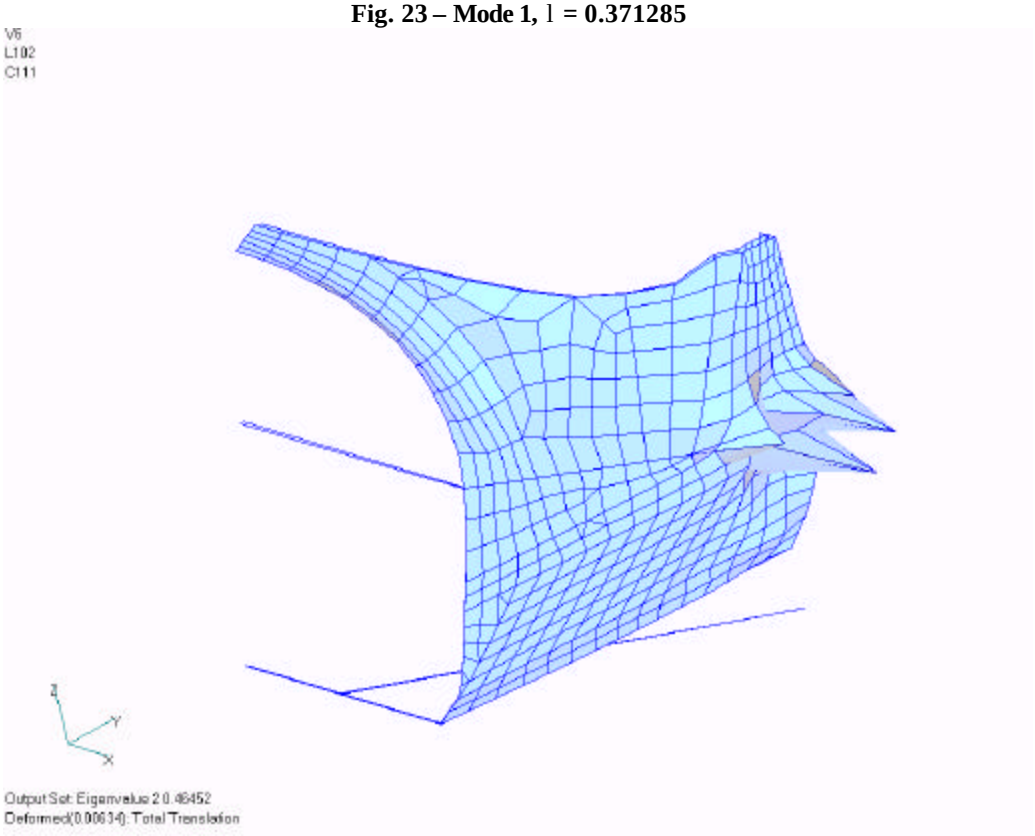

Fig. 24 – Mode 2, λ = 0.46452

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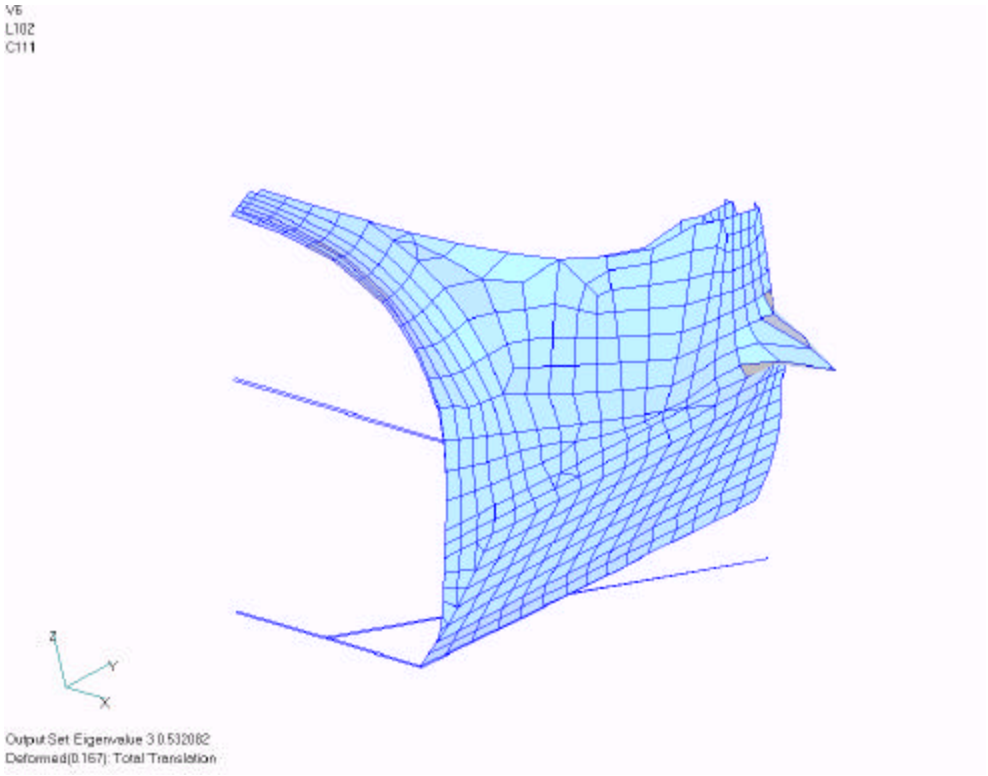

Fig. 25 – Mode 3, l = 0.532082

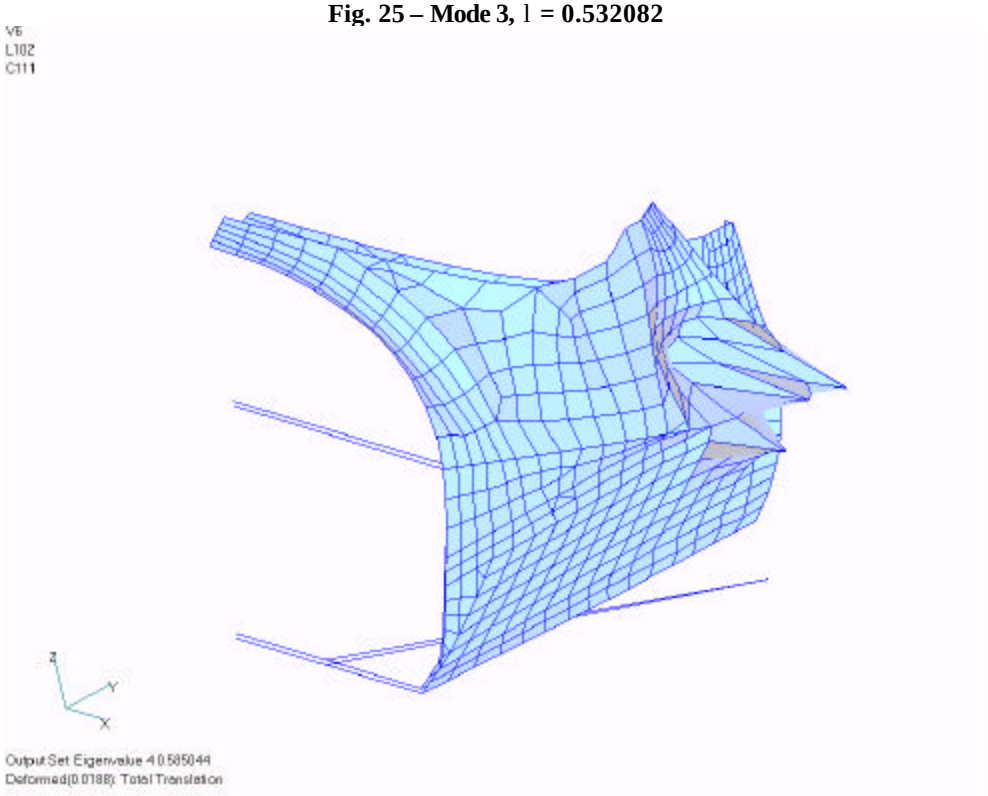

Fig. 26 – Mode 4, l = 0. 585044

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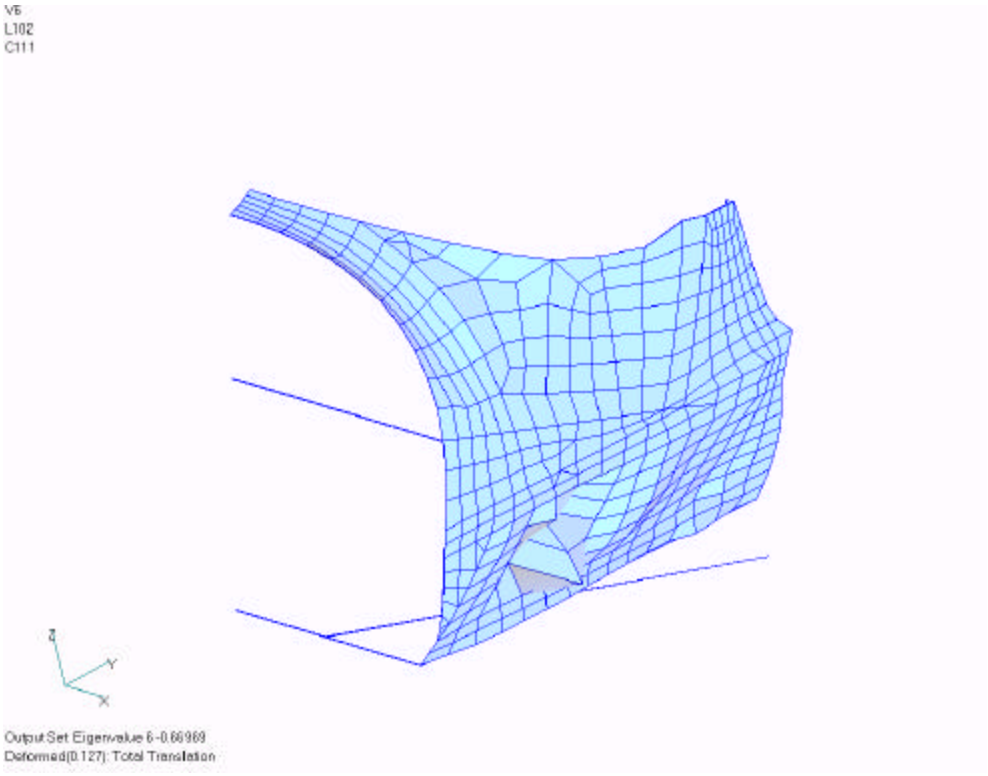

Fig. 27 – Mode 5, λ **= -0.654989**

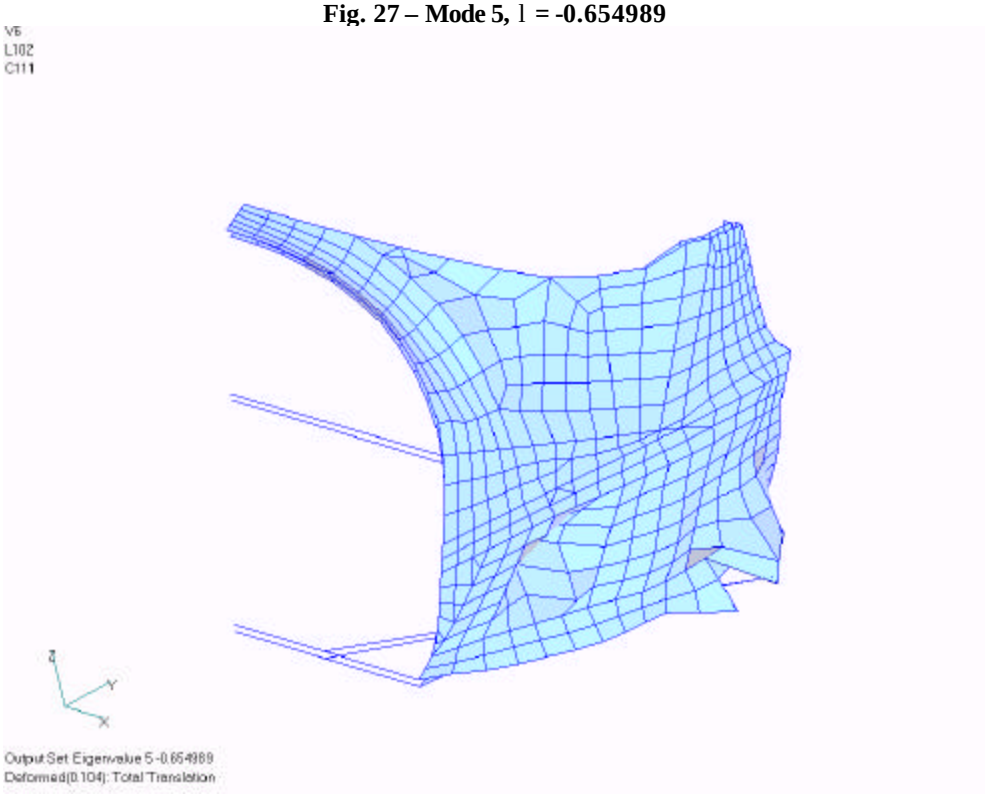

Fig. 28 – Mode 6, λ **= -0.66969**

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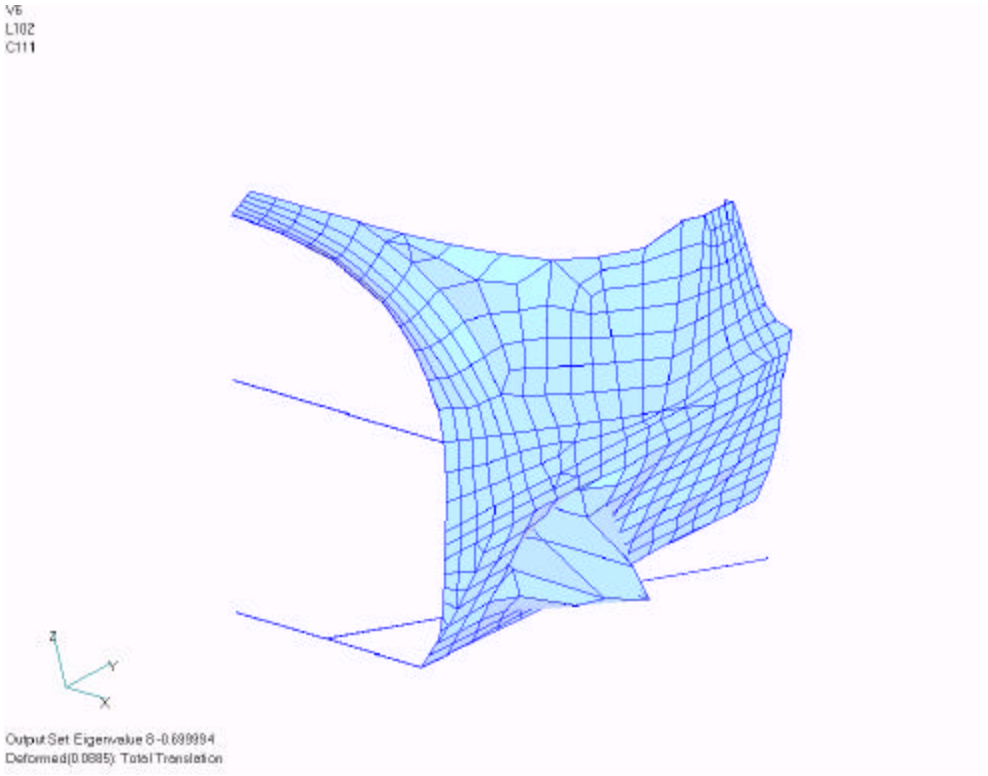

Fig. 29 – Mode 7, l = 0.69686

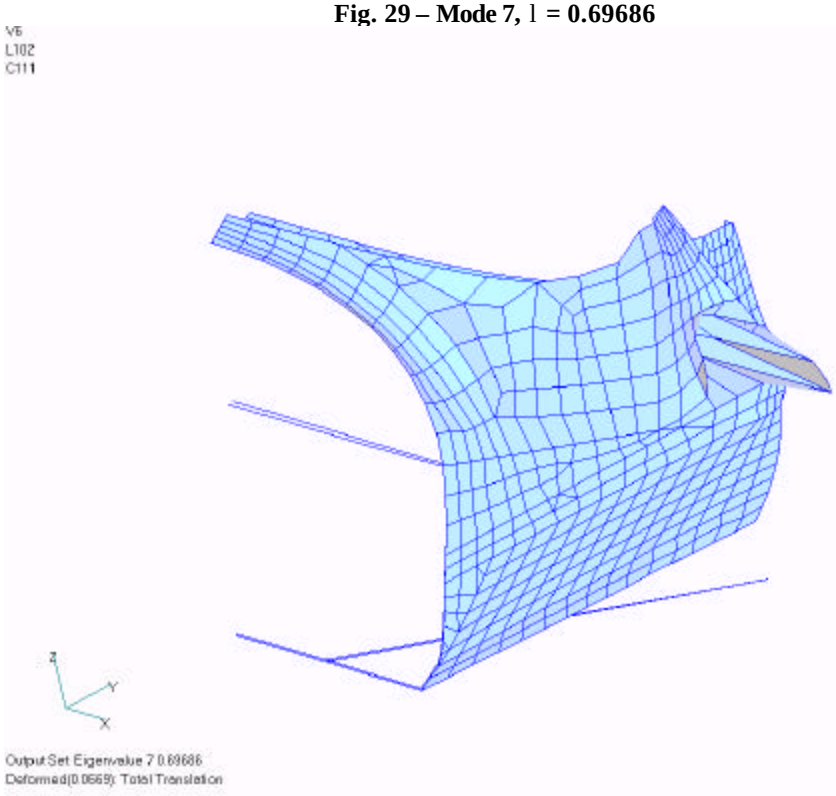

Fig. 30 – Mode 8, l = -0. 699994

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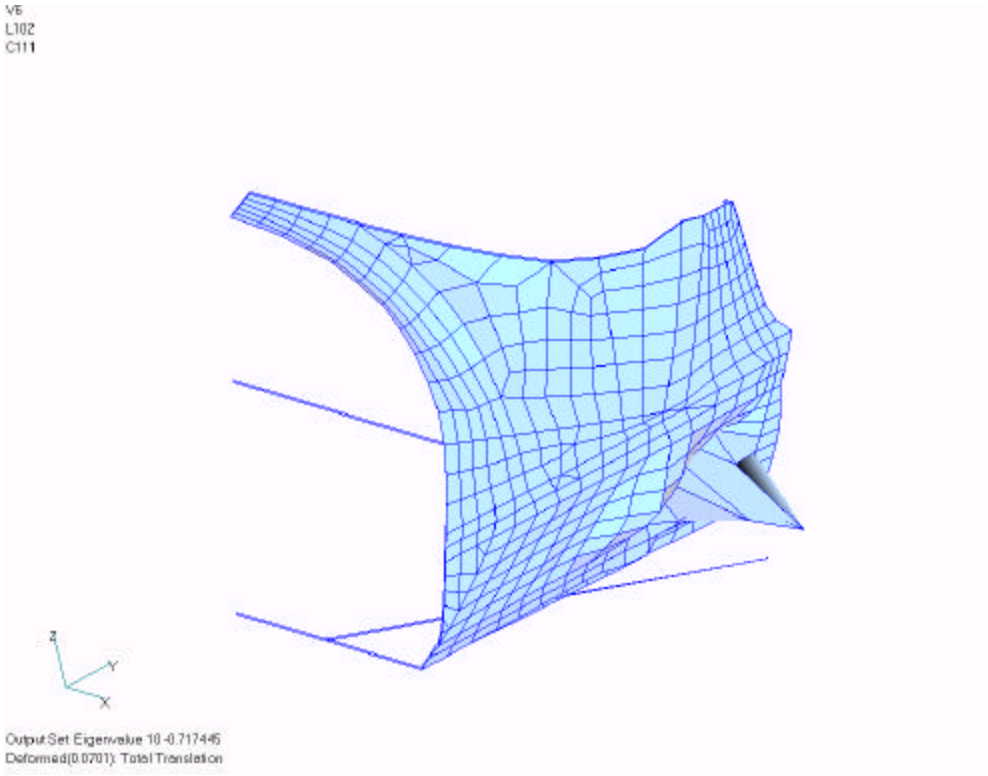

Fig. 31 – Mode 9, λ = -0.70504

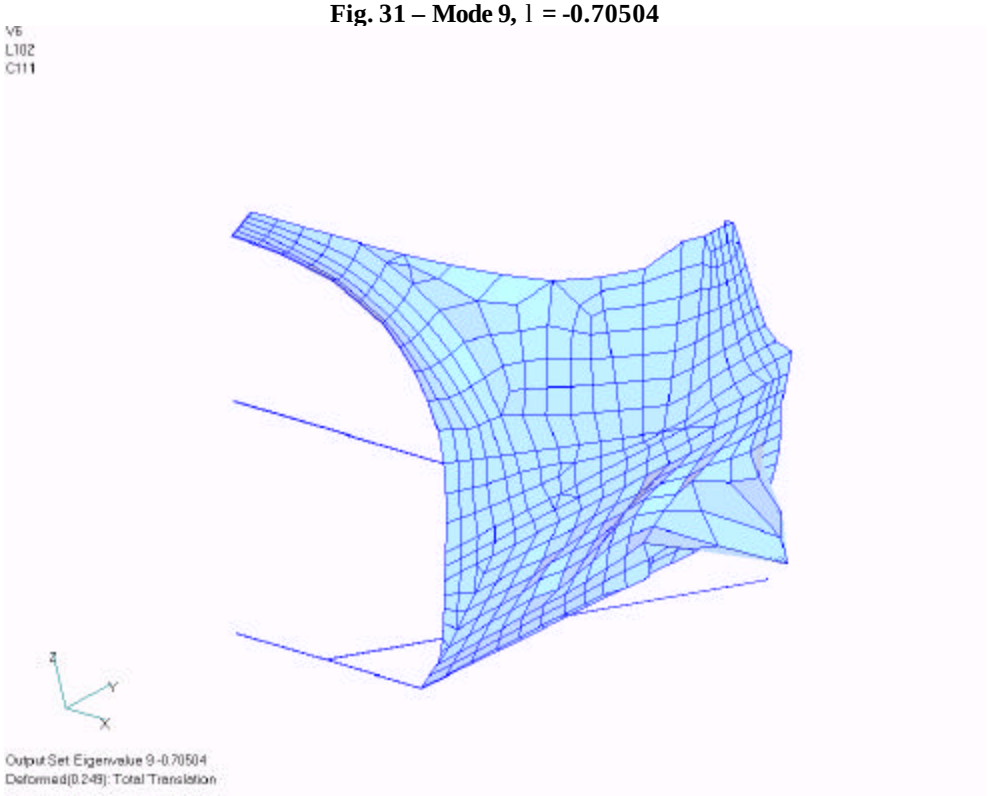

Fig. 32 – Mode 10, λ = -0. 717445

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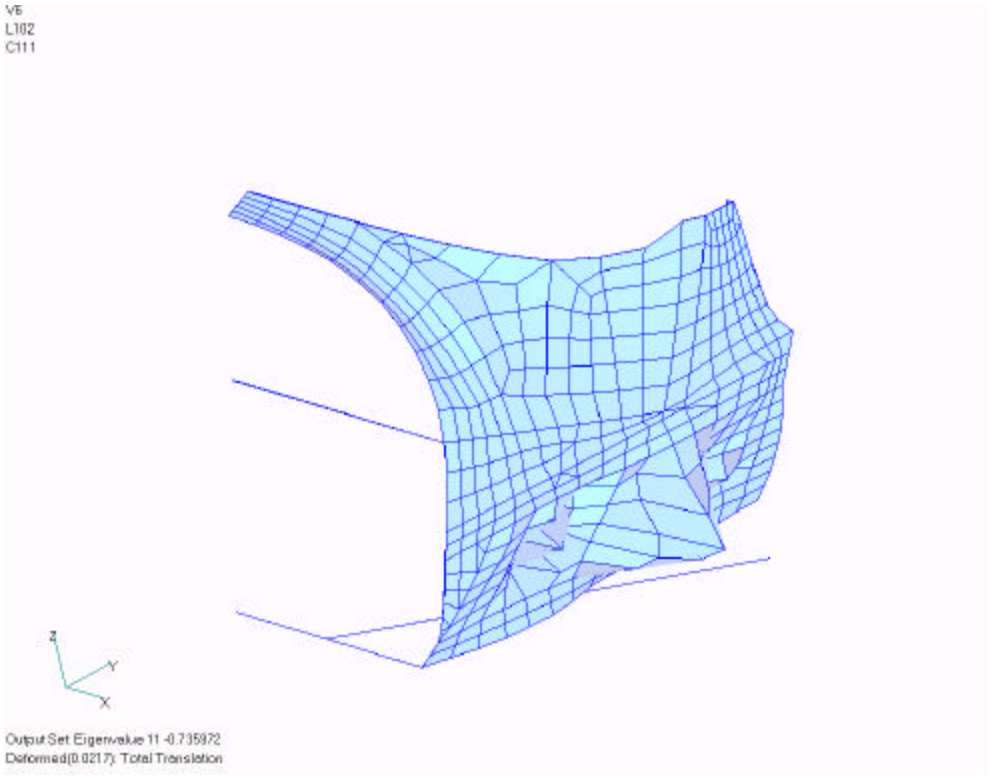

Fig. 33 – Mode 11, λ = -0.735972

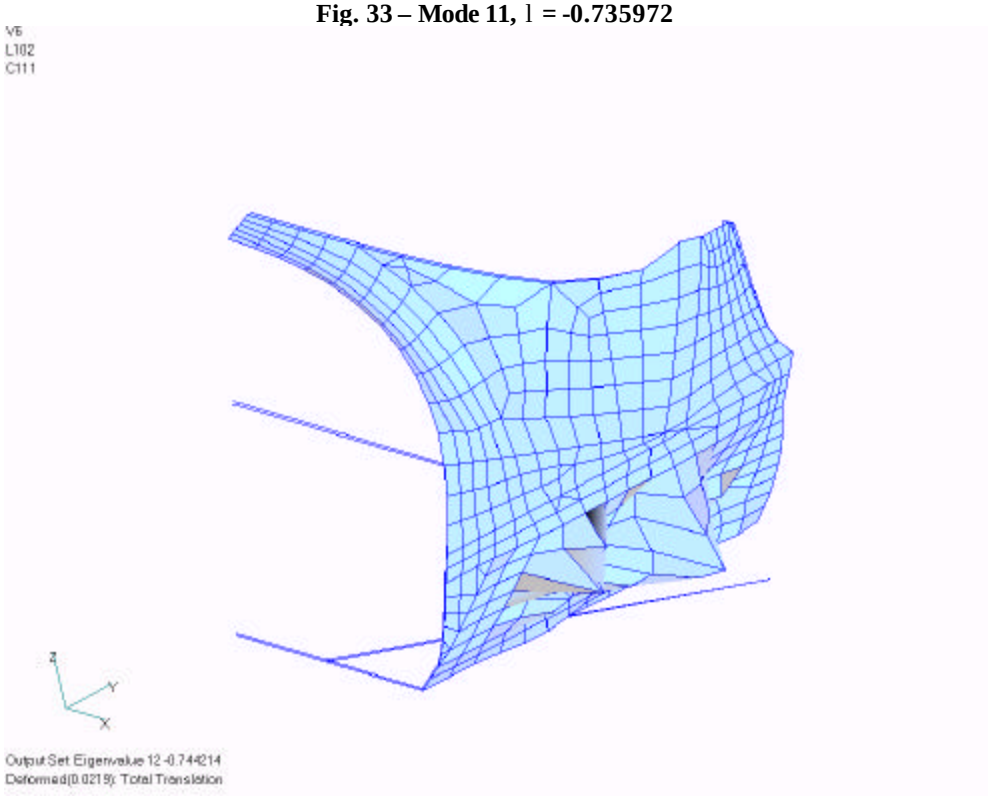

Fig. 34 – Mode 12, λ = -0.744214

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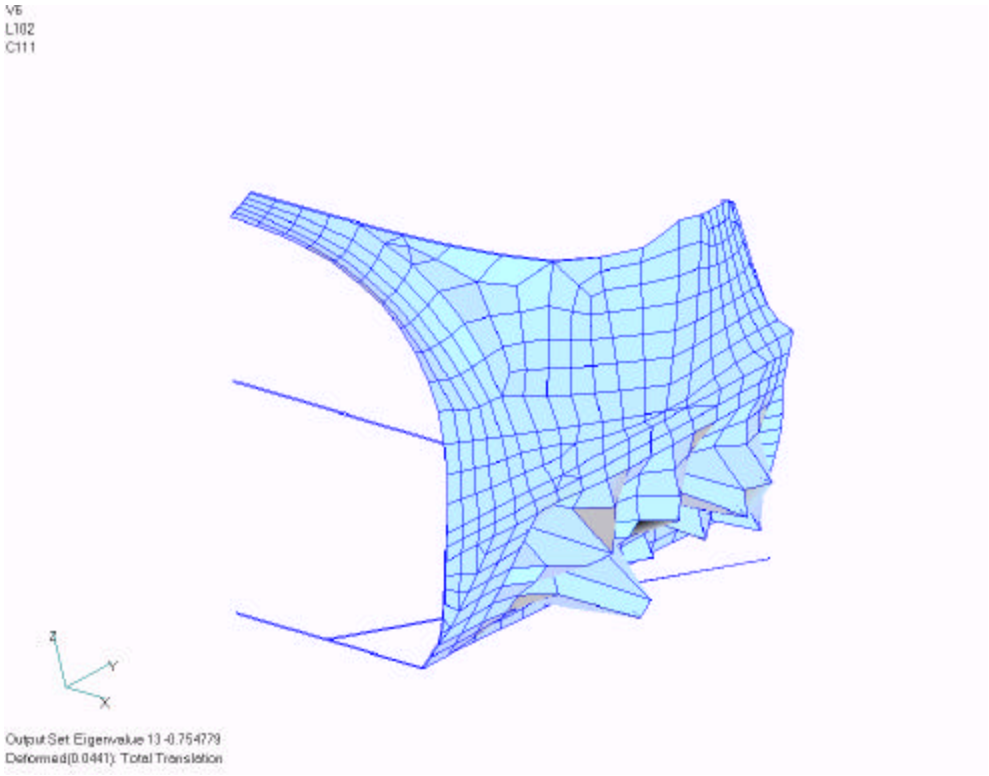

Fig. 35 – Mode 13, λ = -0.754779

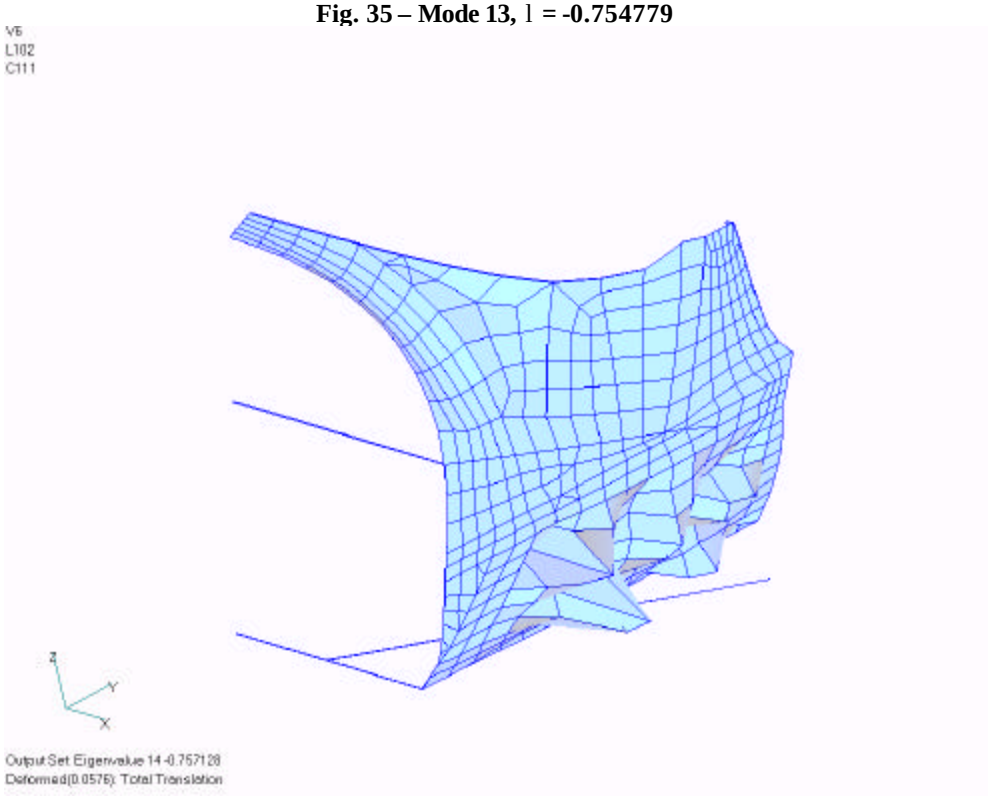

Fig. 36 – Mode 14, λ = -0.757128

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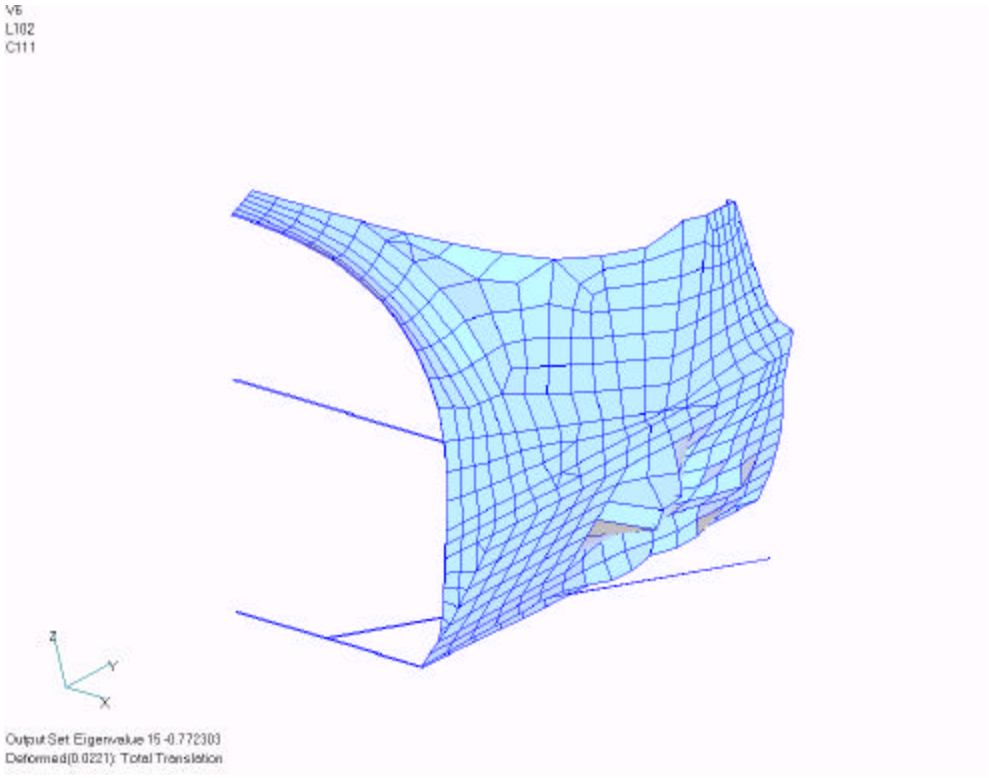

Fig. 37 – Mode 15, λ = -0.772303

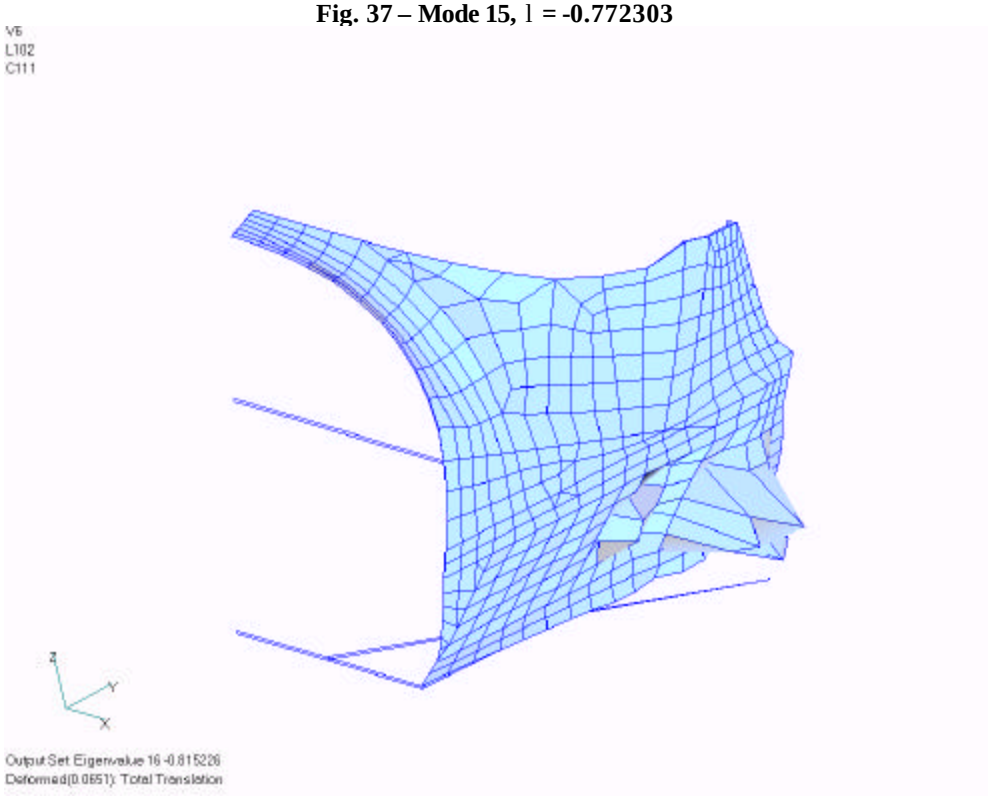

Fig. 38 – Mode 16, λ = -0.815226

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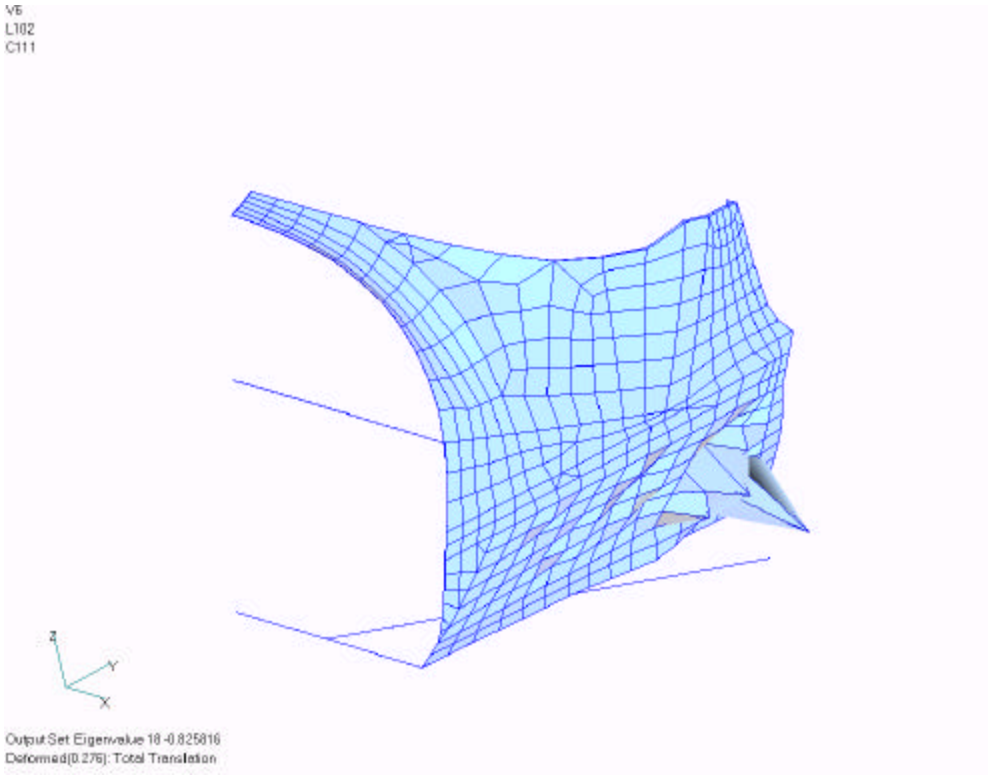

Fig. 39 – Mode 17, λ = -0.820155

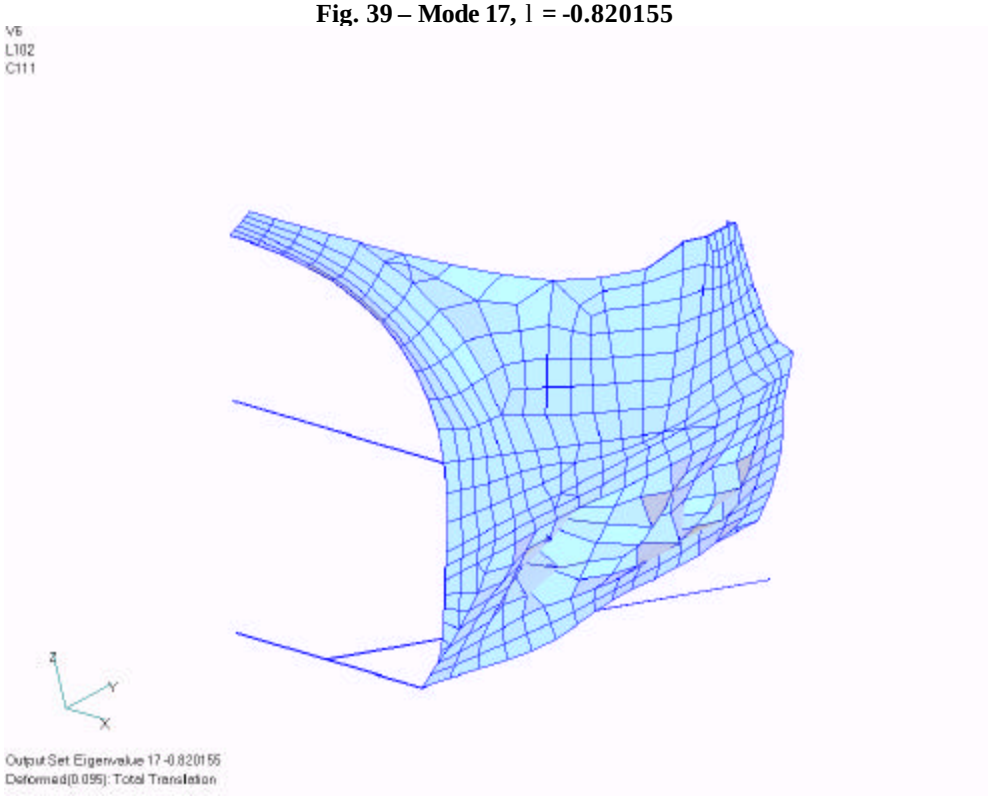

Fig. 40 – Mode 18, λ = -0. 825816

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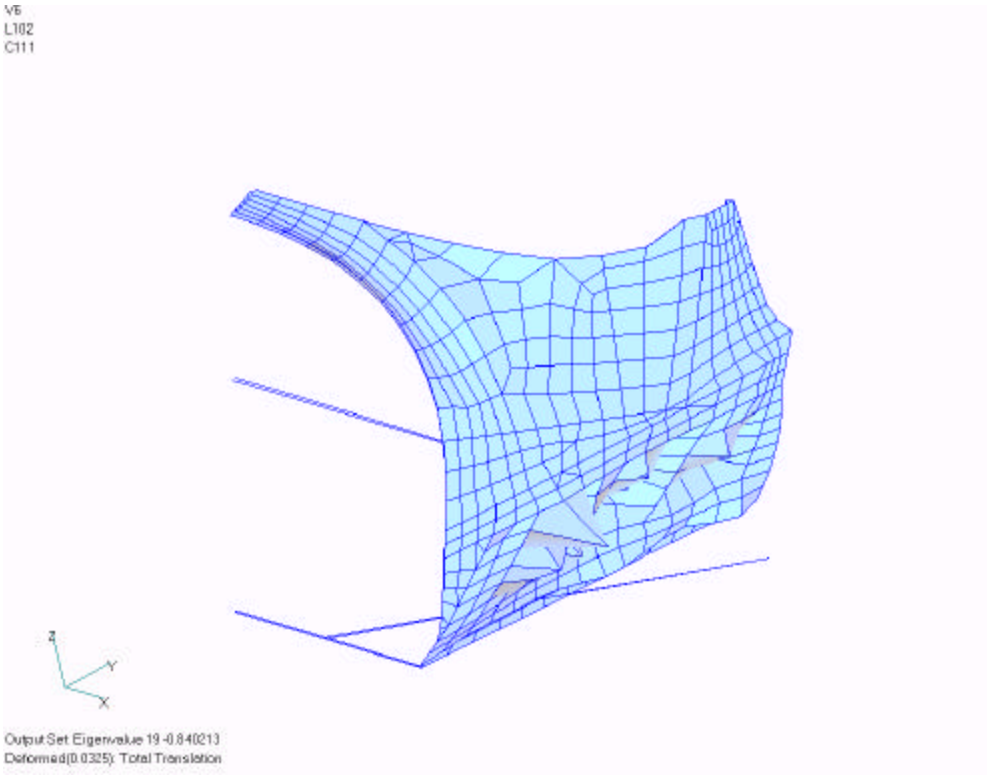

Fig. 41 – Mode 19, λ = -0. 840213

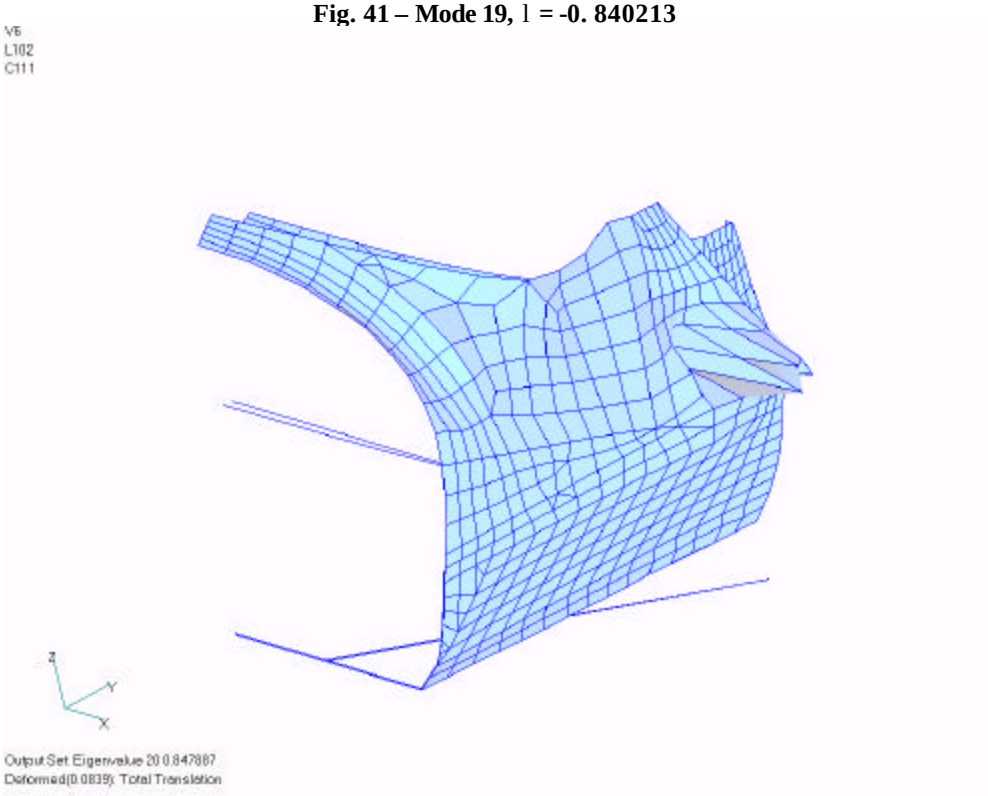

Fig. 42 – Mode 20, λ = 0.847887

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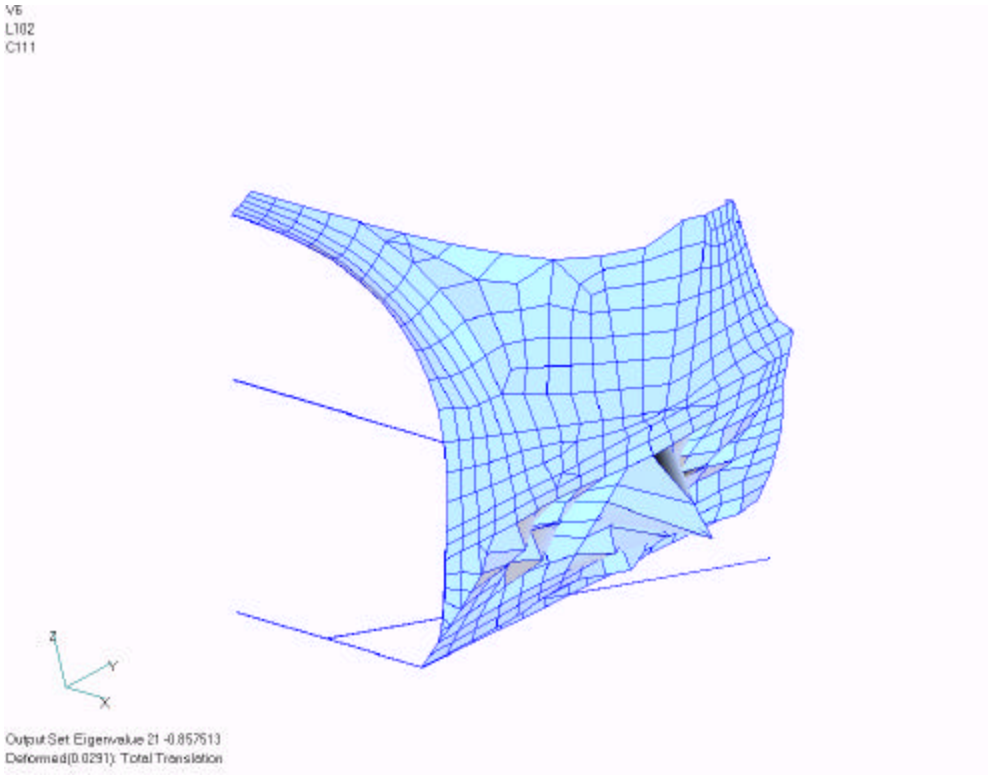

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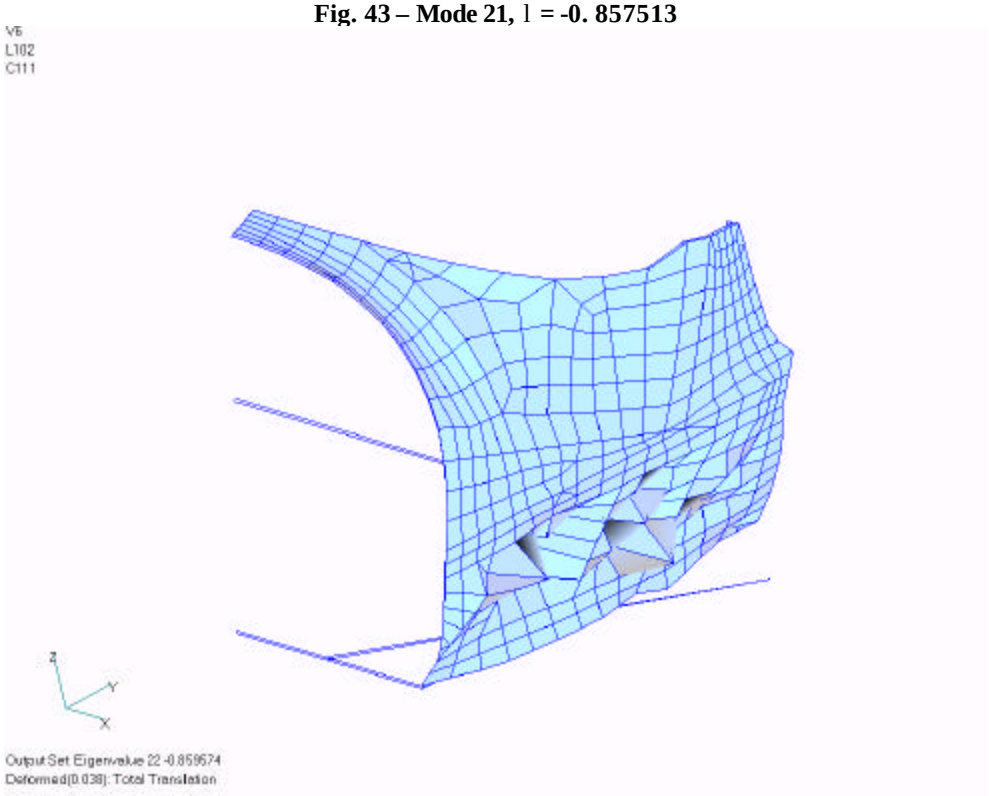

Fig. 44 – Mode 22, λ = -0.859574

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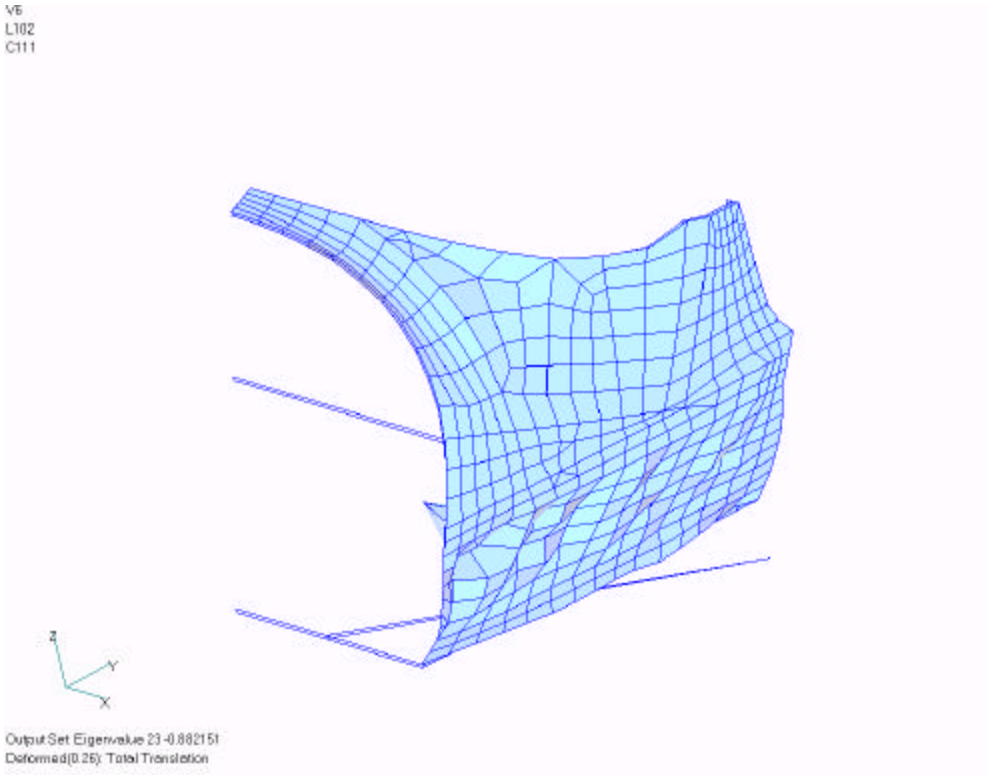

Fig. 45 – Mode 23, l = -0. 882151

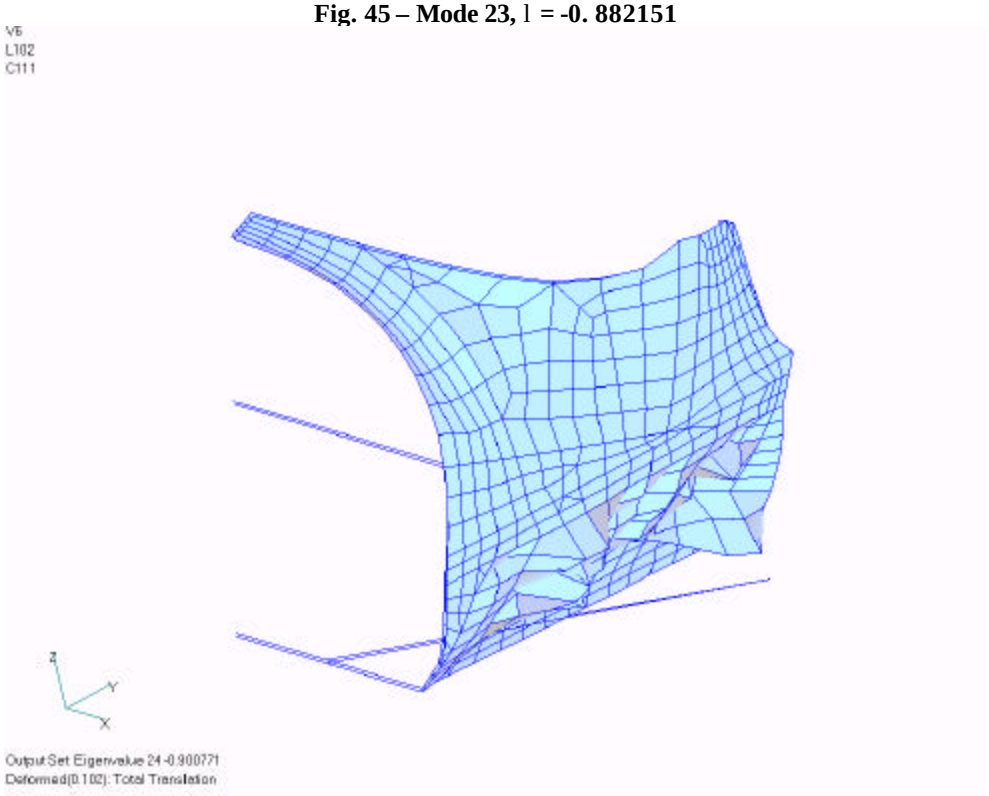

Fig. 46 – Mode 24, l = -0. 900771

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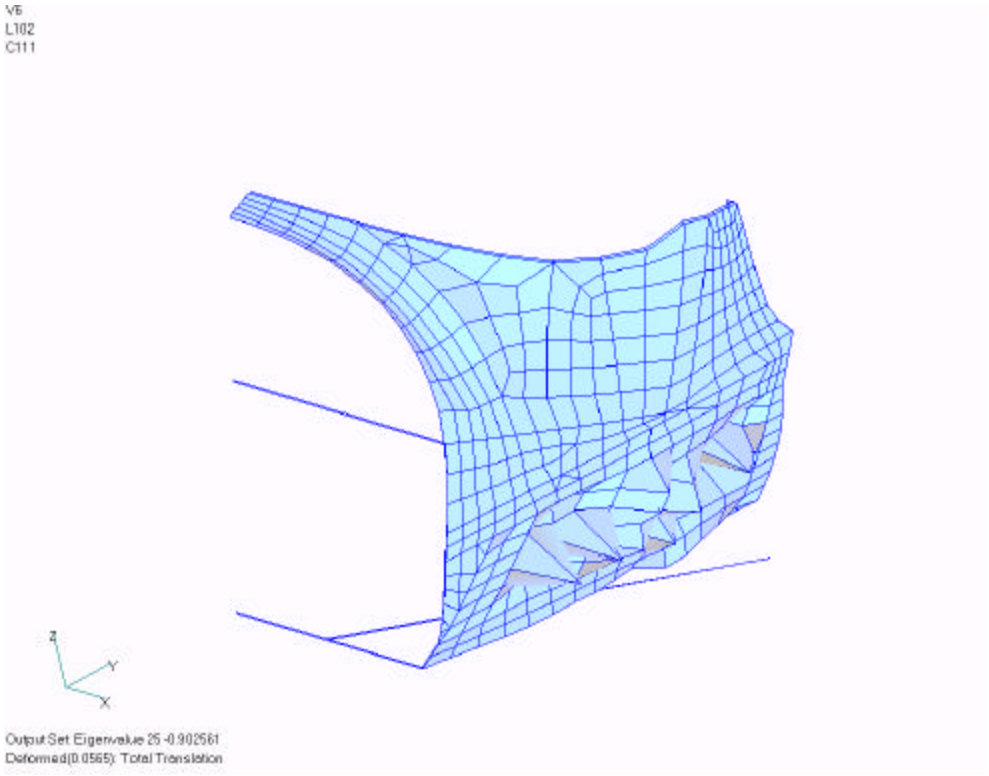

Fig. 47 – Mode 25, λ = -0. 902561

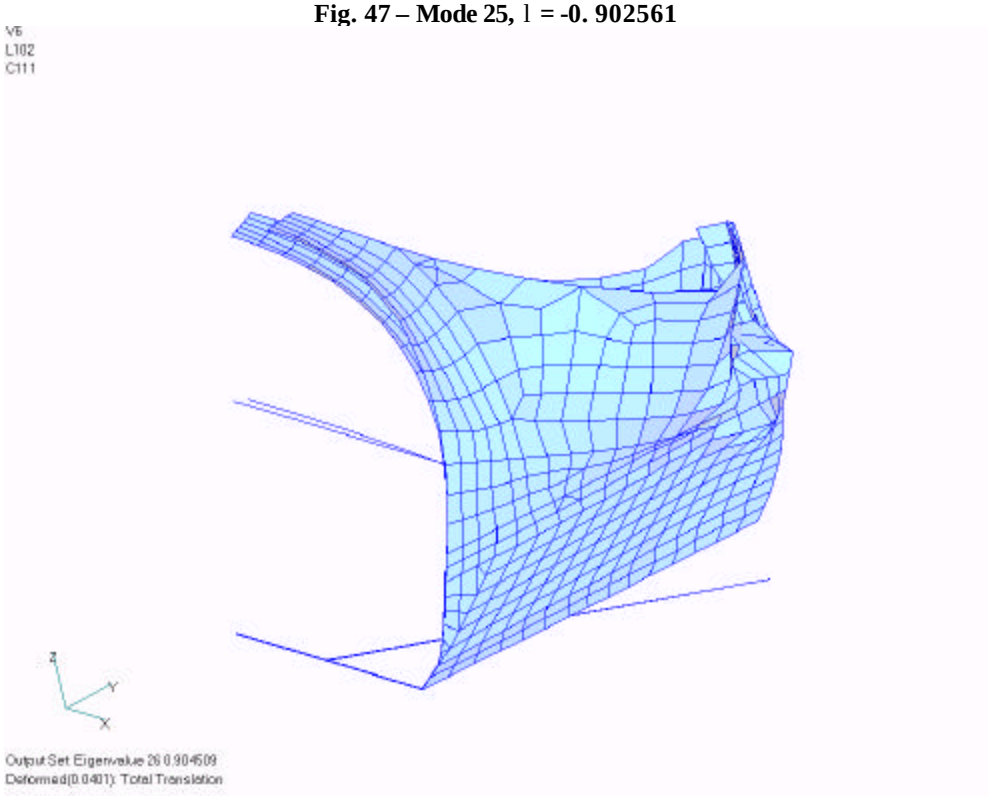

Fig. 48 – Mode 26, λ = 0.904509

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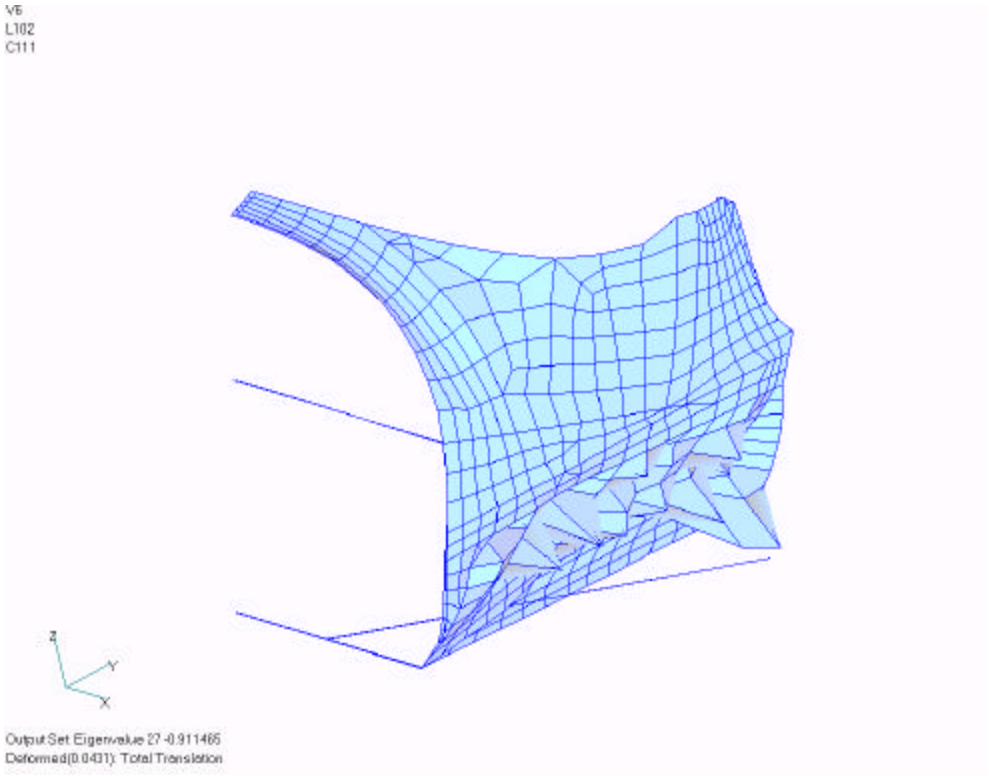

Fig. 49 – Mode 27, λ = -0. 911465

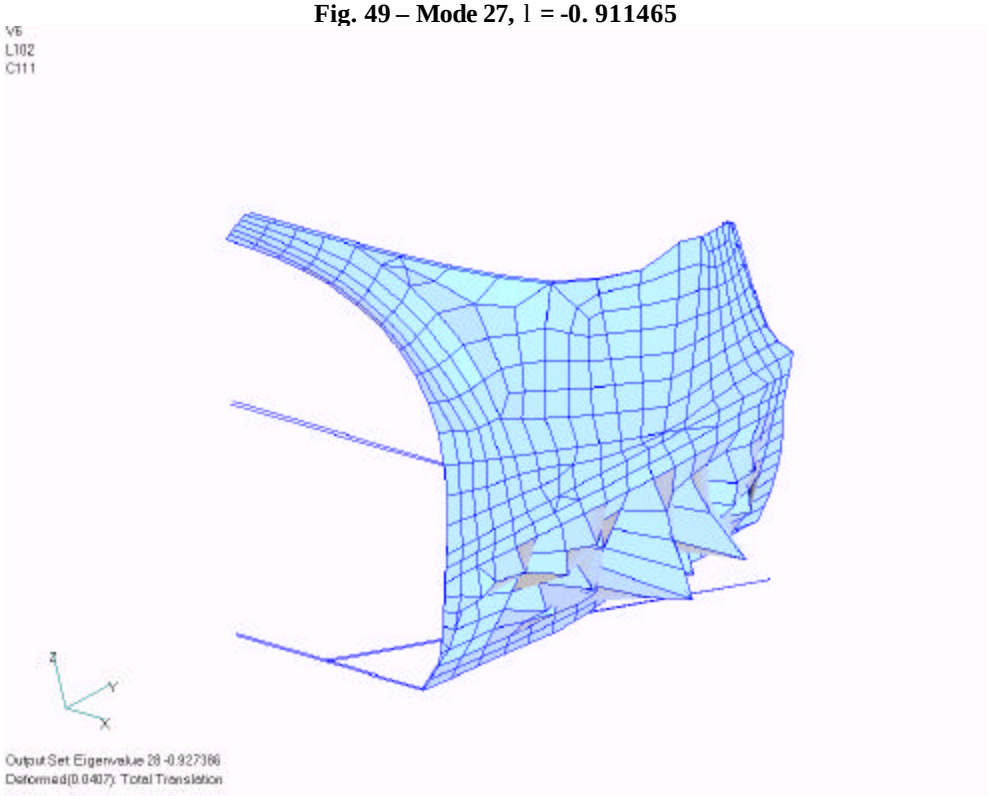

Fig. 50 – Mode 28, λ = -0. 927386

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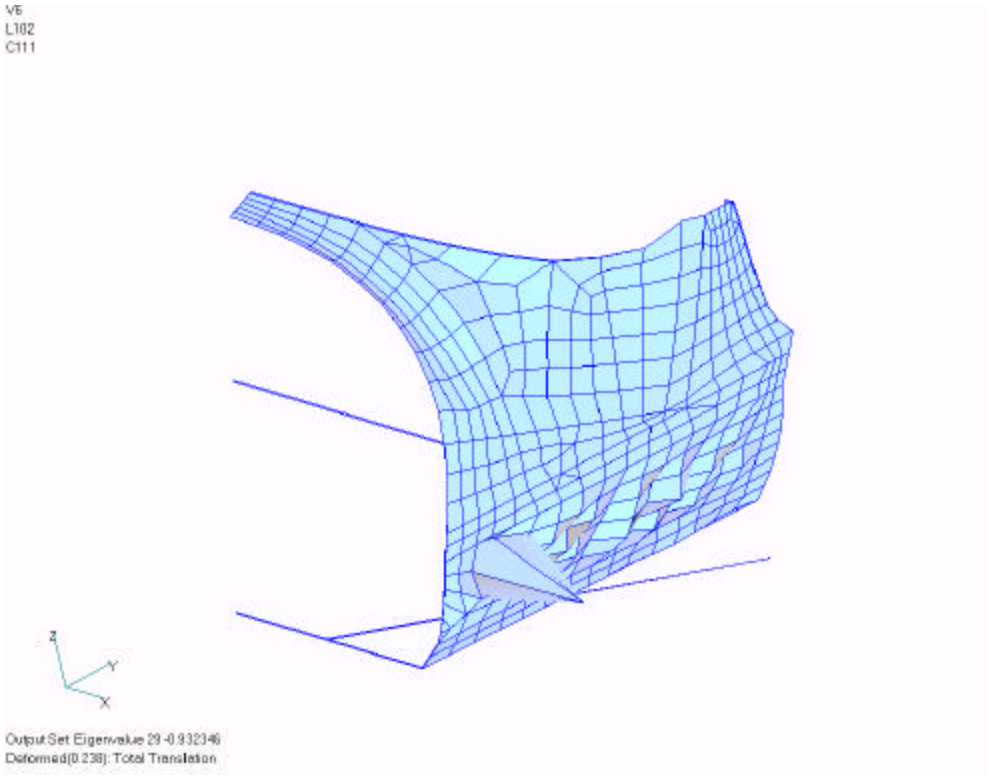

Fig. 51 – Mode 29, λ = -0. 932346

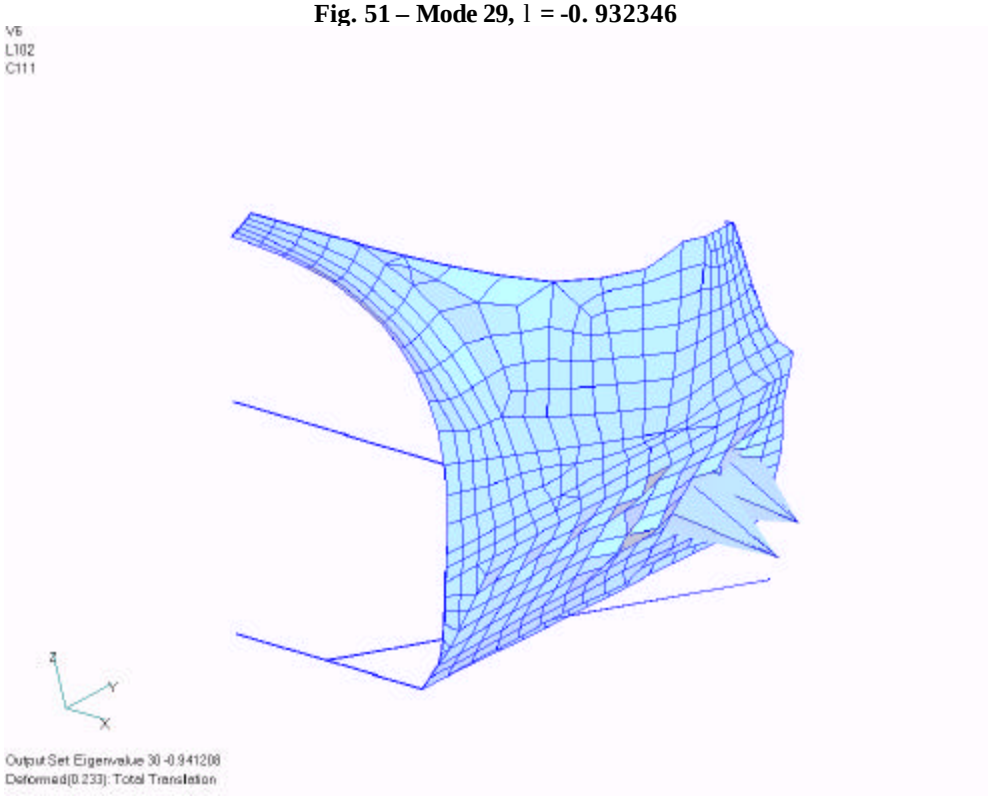

Fig. 52 – Mode 30, λ = -0.941208

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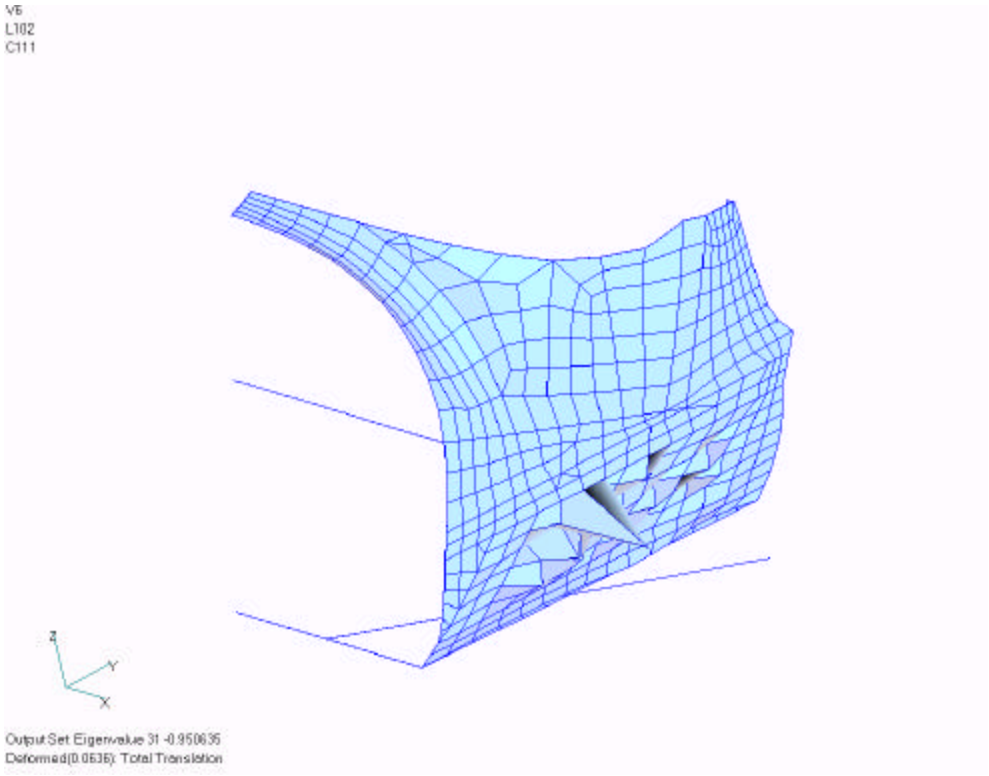

Fig. 53 – Mode 31, λ = -0. 950635

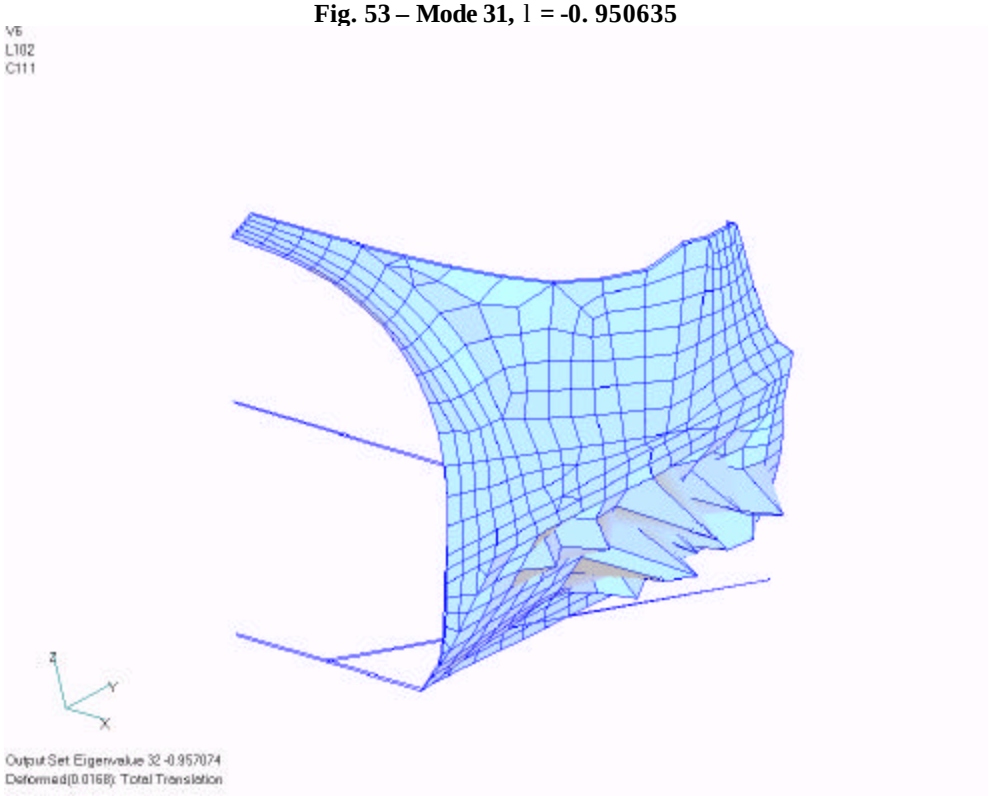

Fig. 54 – Mode 32, λ = -0. 957074

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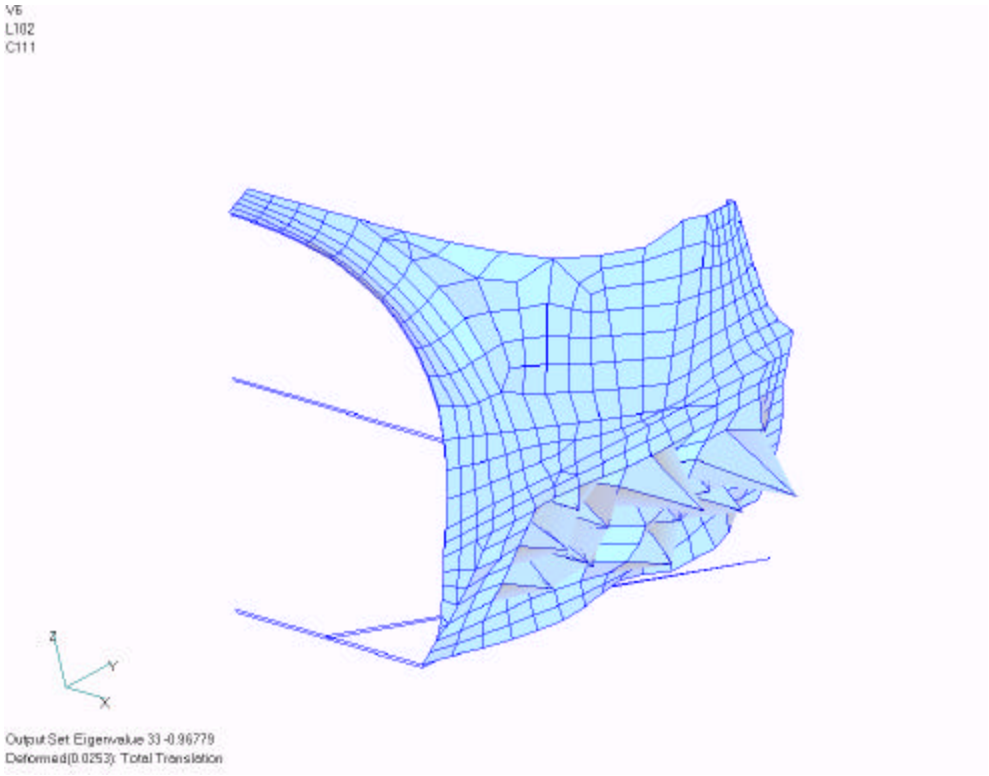

Fig. 55 – Mode 33, λ = -0. 96779

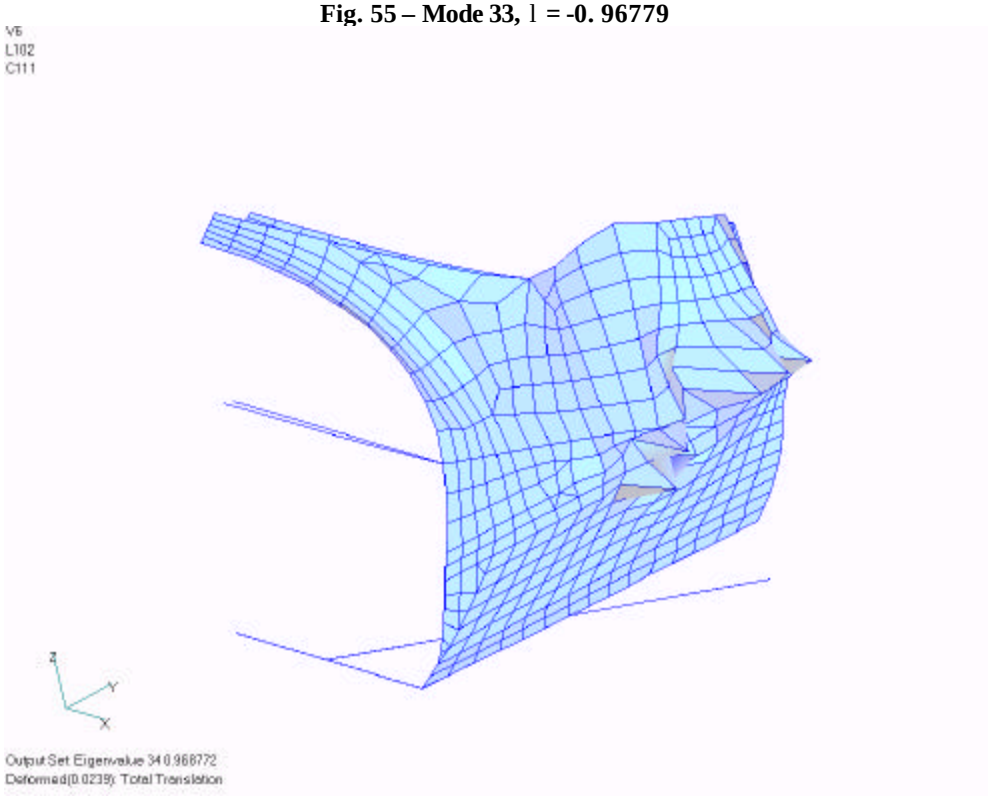

Fig. 56 – Mode 34, λ = 0.968772

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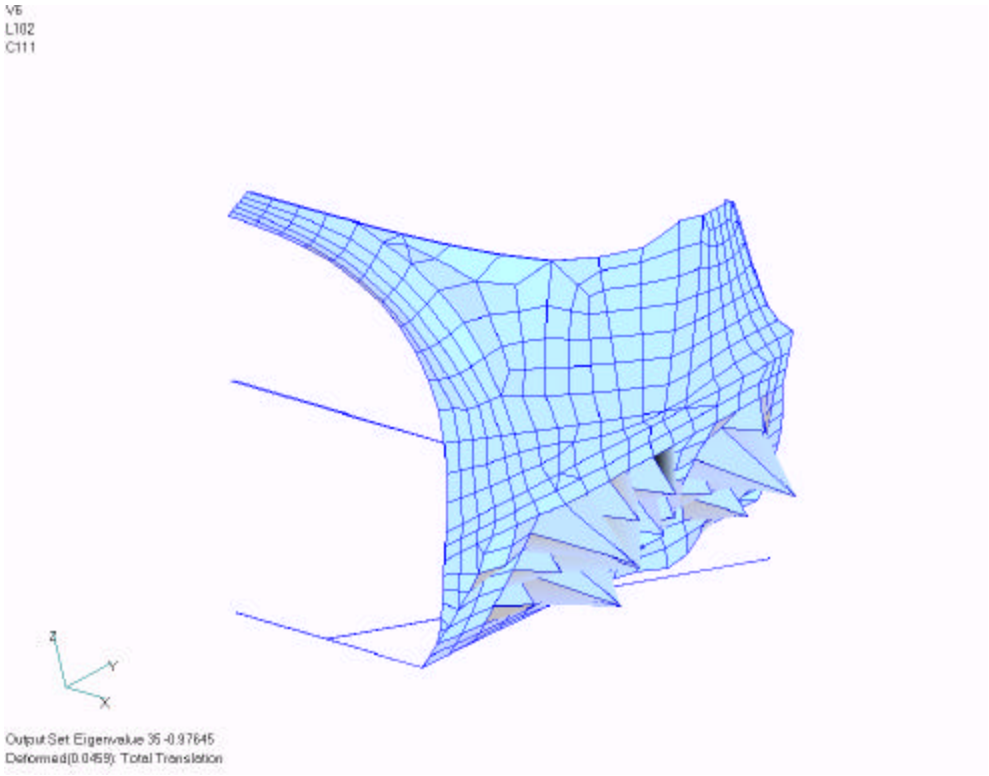

Fig. 57 – Mode 35, l = -0. 97645

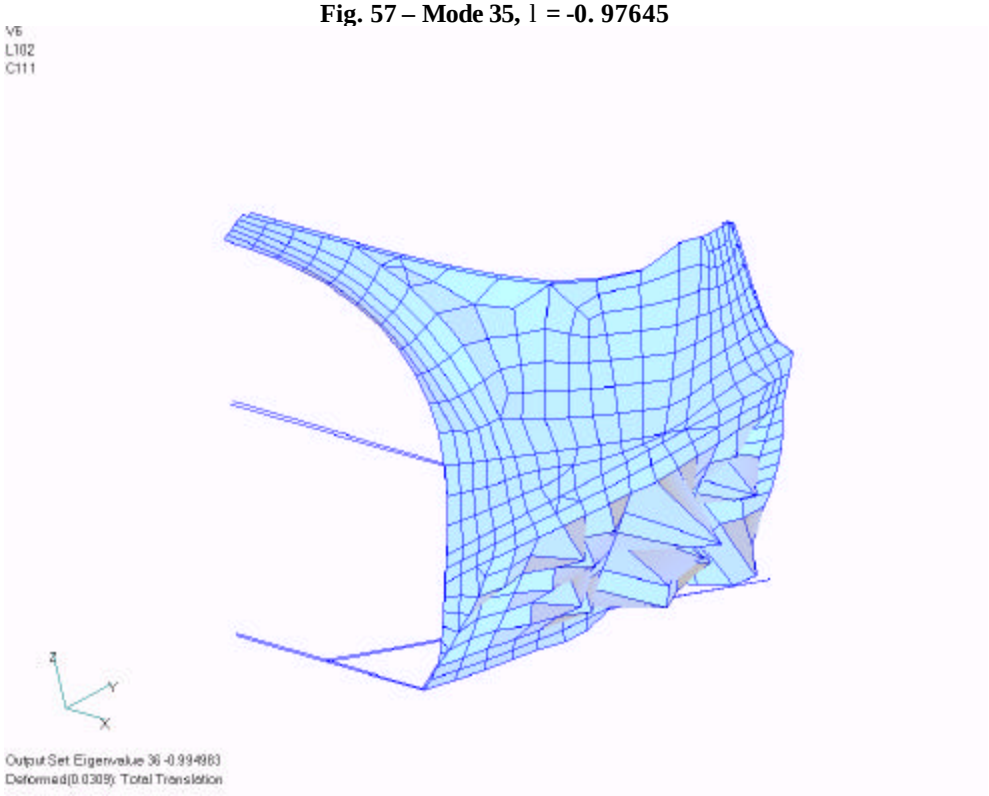

Fig. 58 – Mode 36, l = -0. 994983

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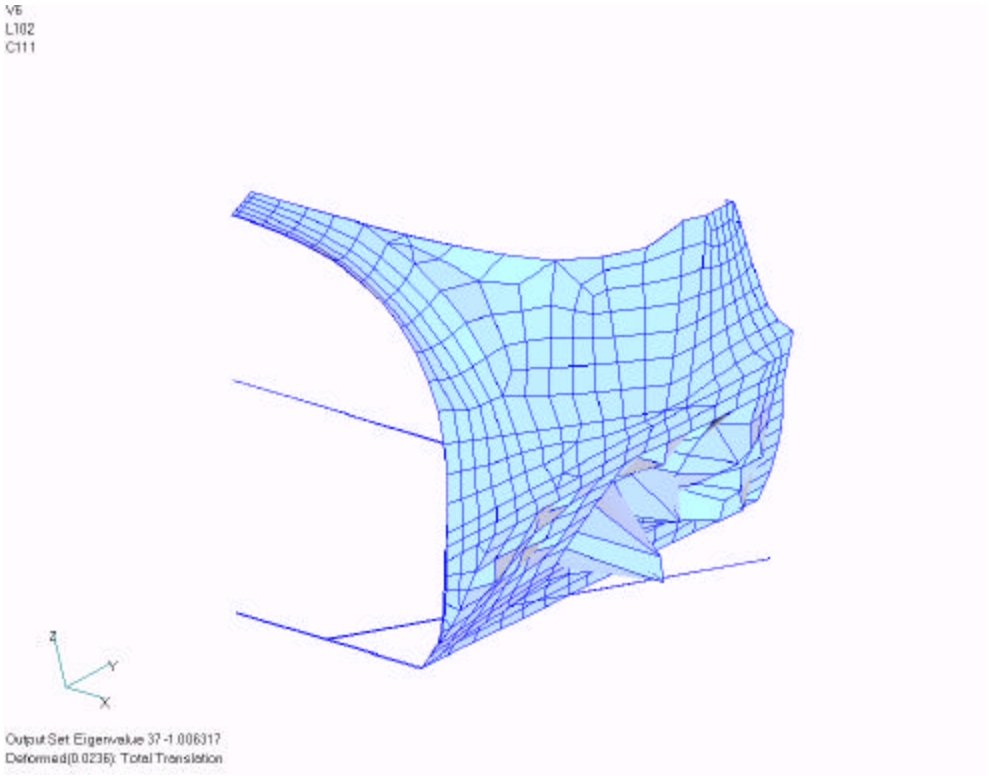

Fig. 59 – Mode 37, λ = -1.006317

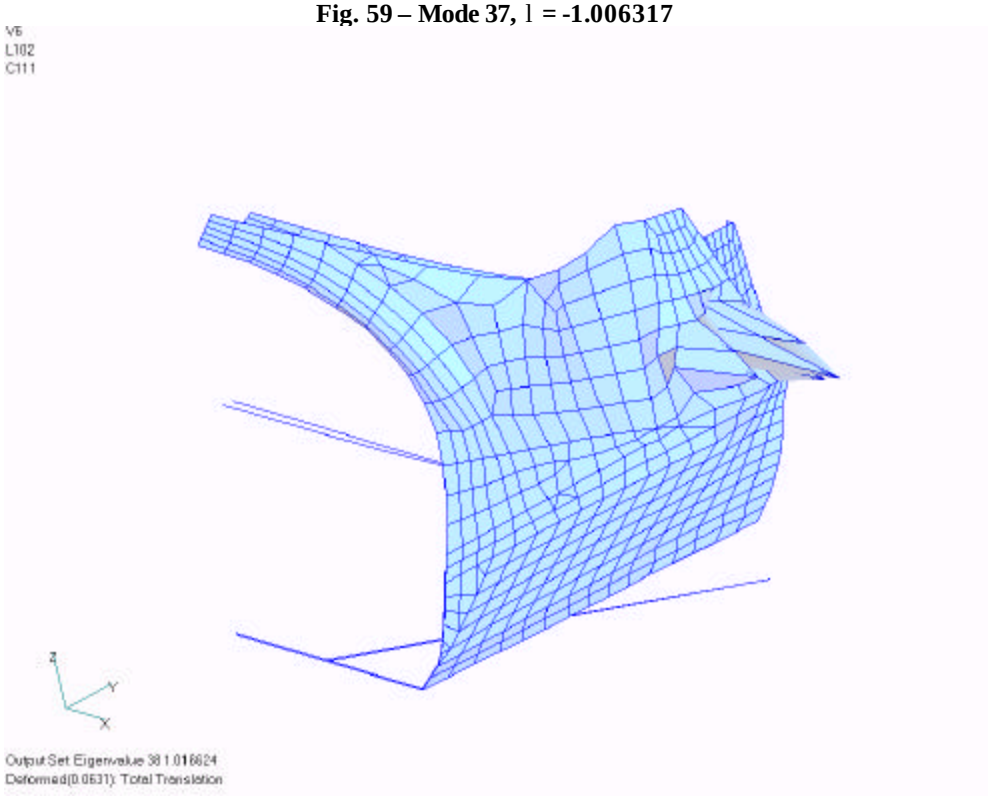

Fig. 60 – Mode 38, λ = 1.016624

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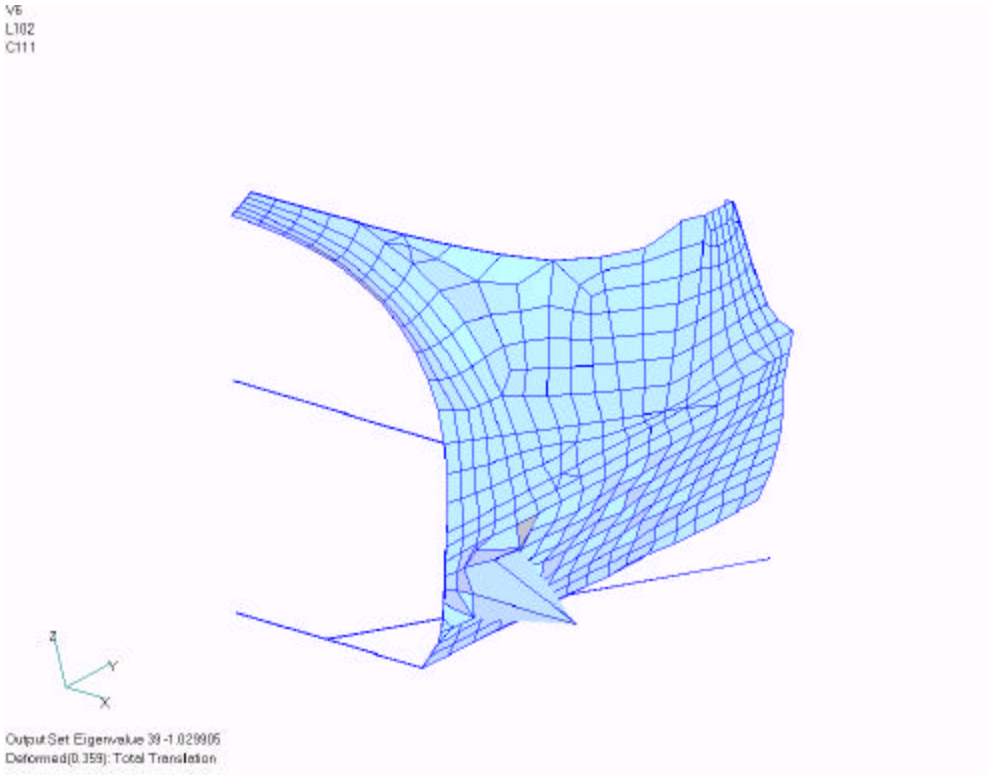

Fig. 61 – Mode 39, λ = -1.029905

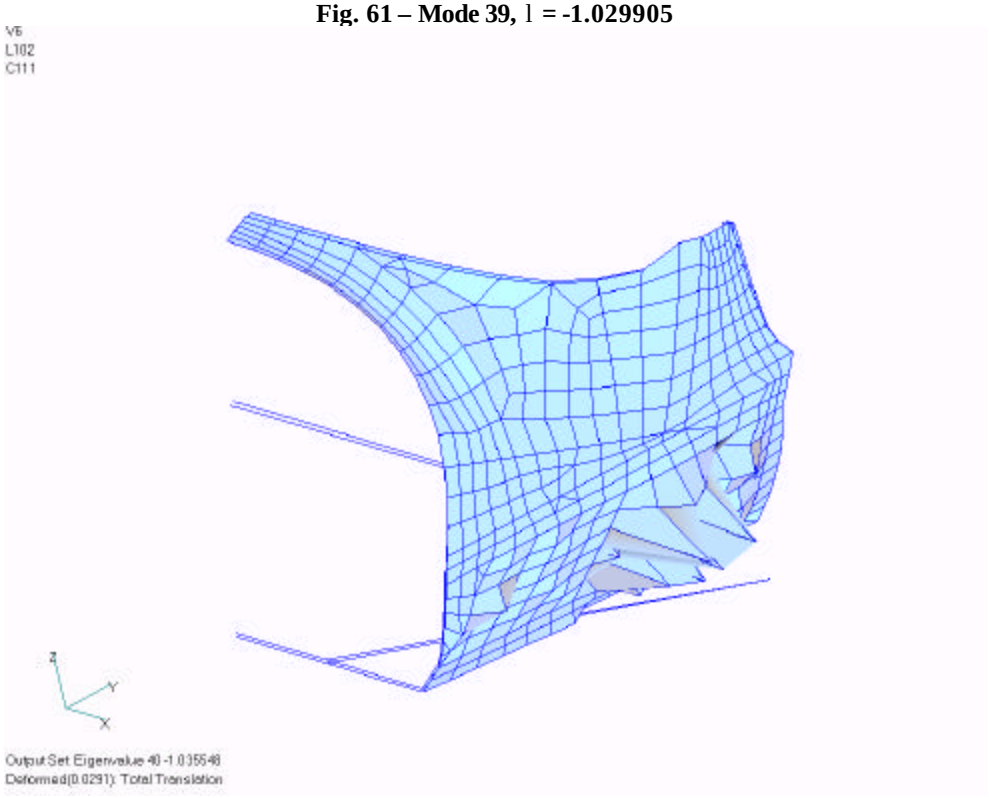

Fig. 62 – Mode 40, λ = -1.035548

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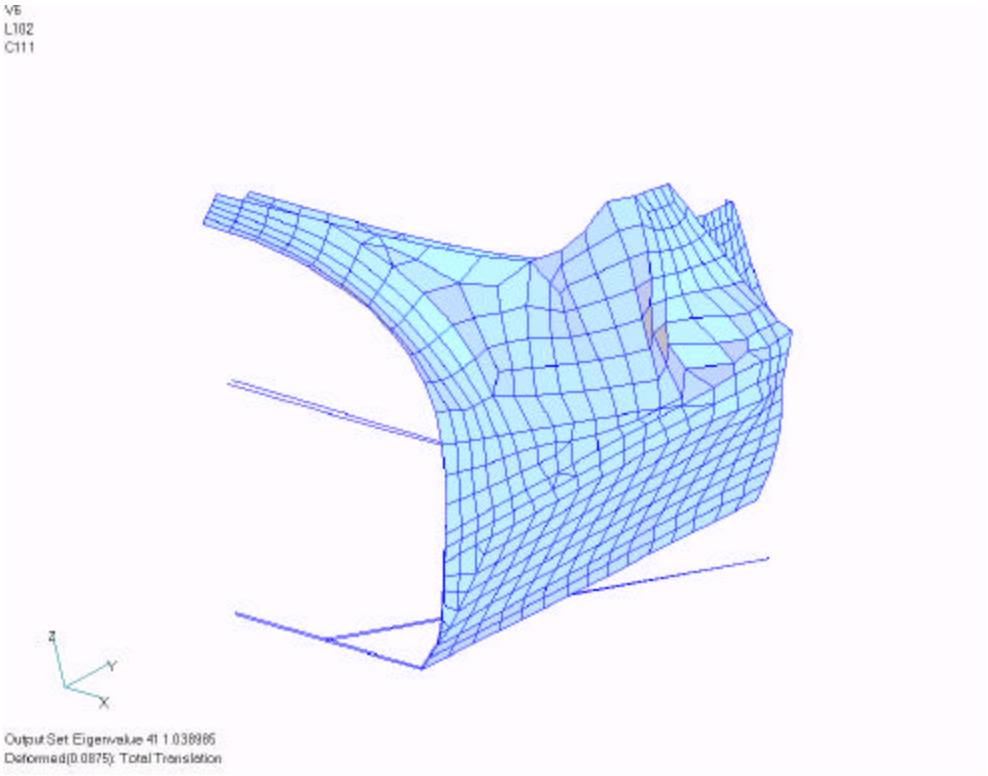

Fig. 63 – Mode 41, λ = 1.038985

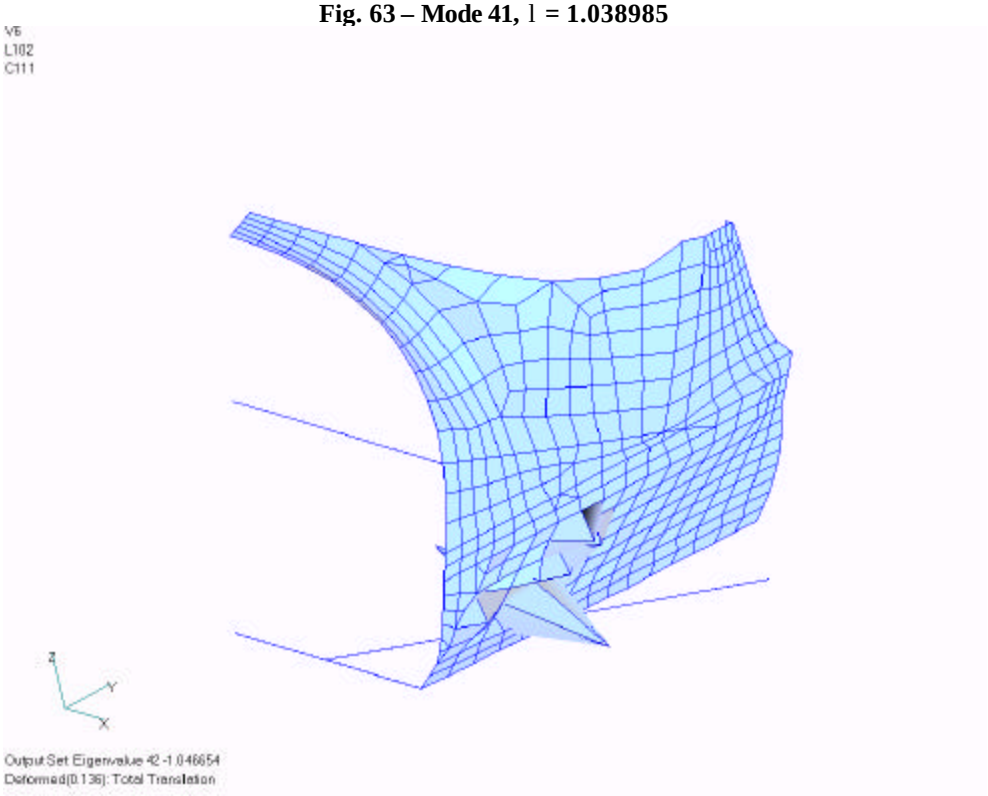

Fig. 64 – Mode 42, λ = -1.046654

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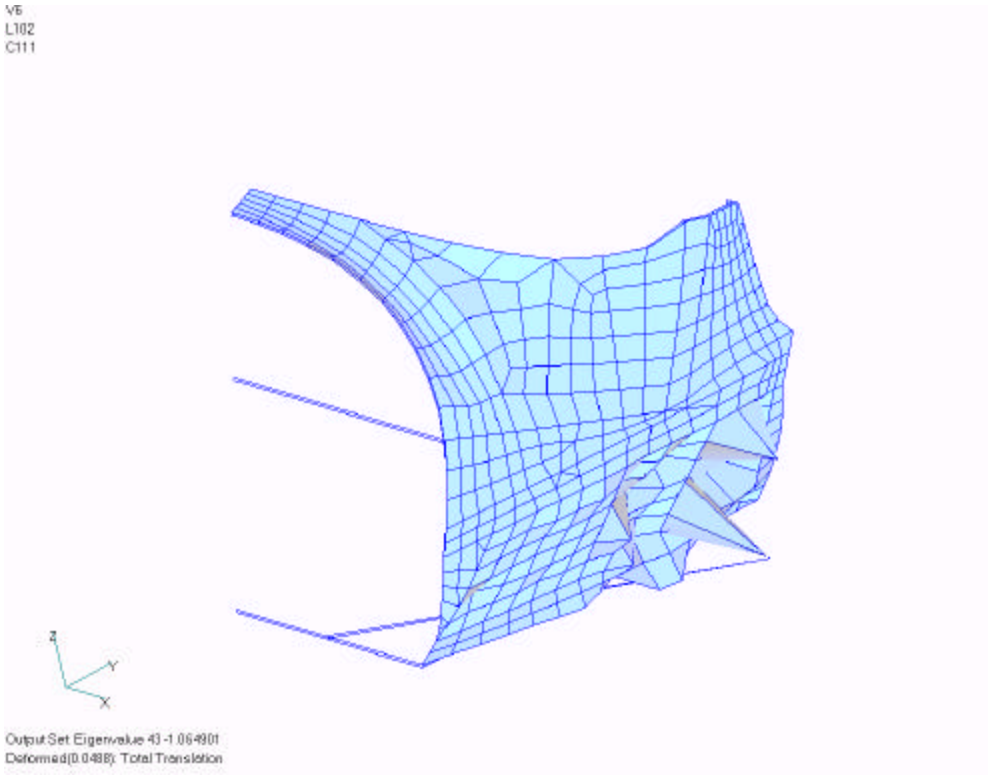

Fig. 65 – Mode 43, λ = -1.064901

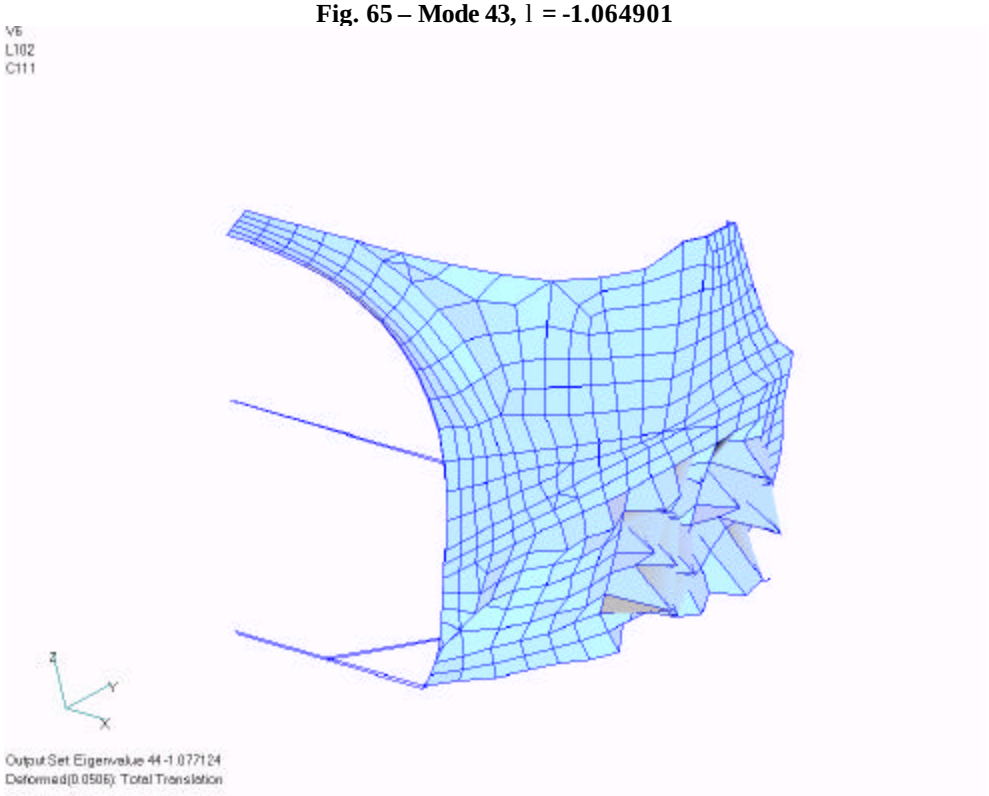

Fig. 66 – Mode 44, λ = -1.077124

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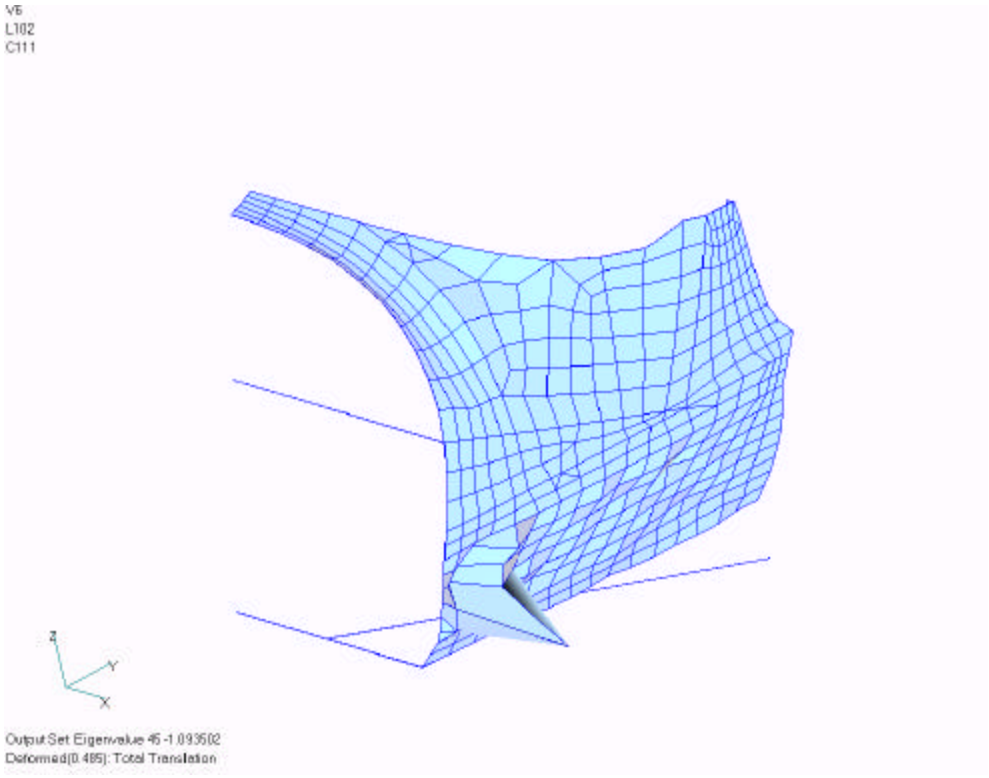

Fig. 67 – Mode 45, λ = -1.093502

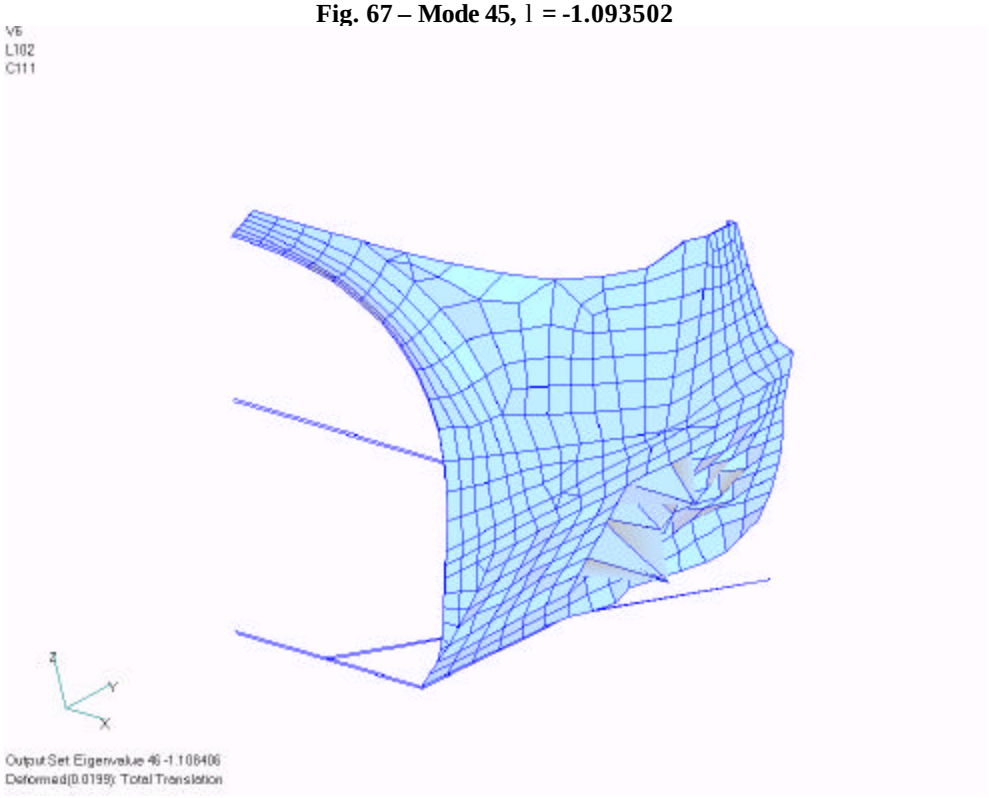

Fig. 68 – Mode 46, λ = -1.108406

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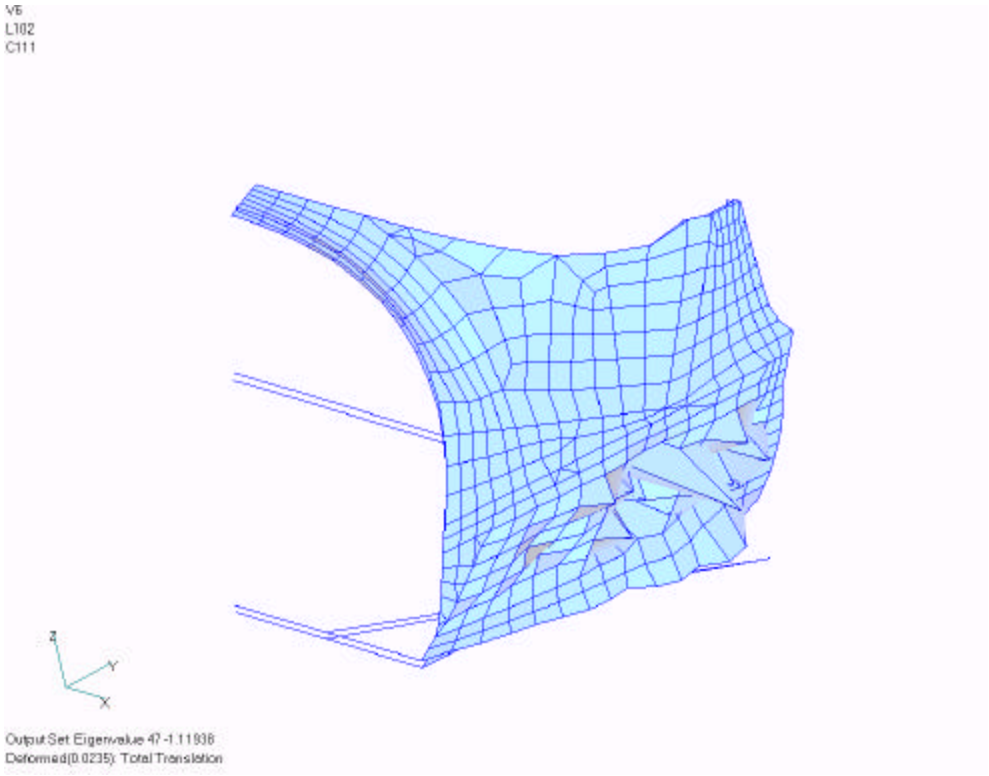

Fig. 69 – Mode 47, λ = -1.11938

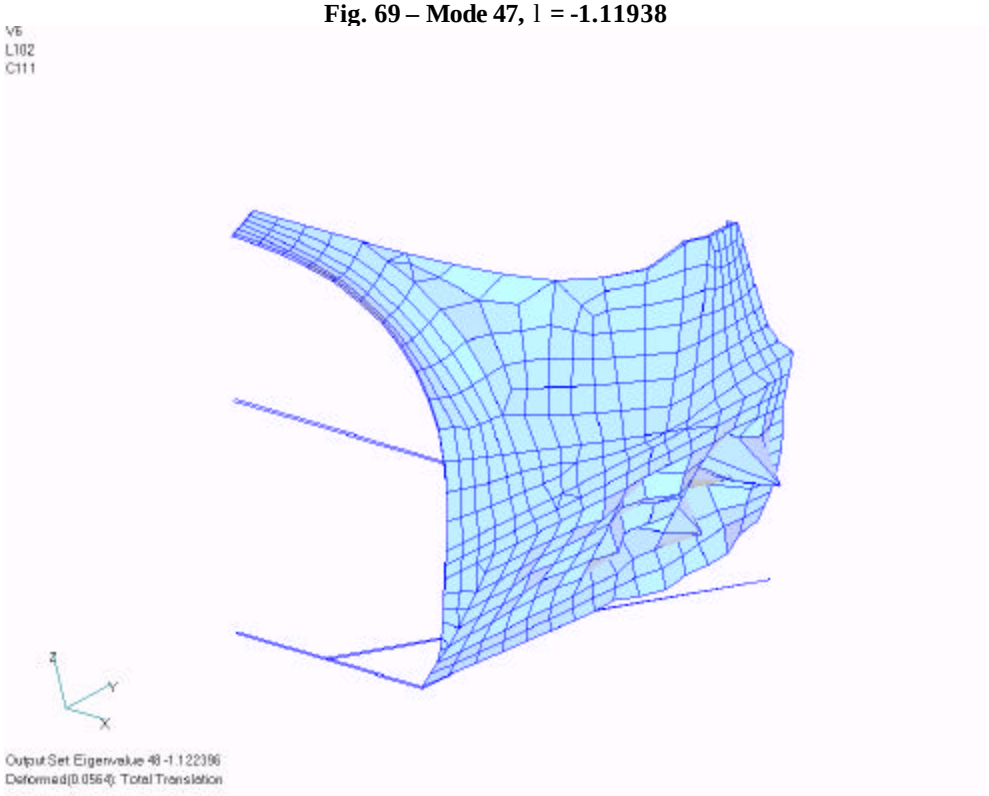

Fig. 70 – Mode 48, λ = -1.122396

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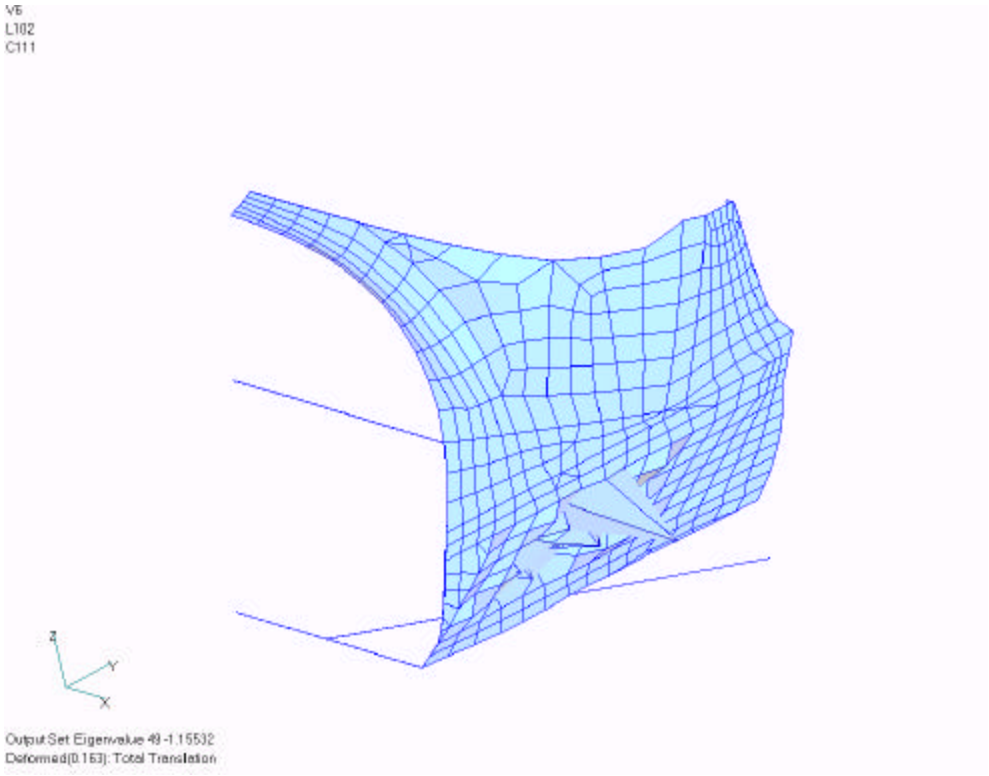

Fig. 71 – Mode 49, λ = -1.15532

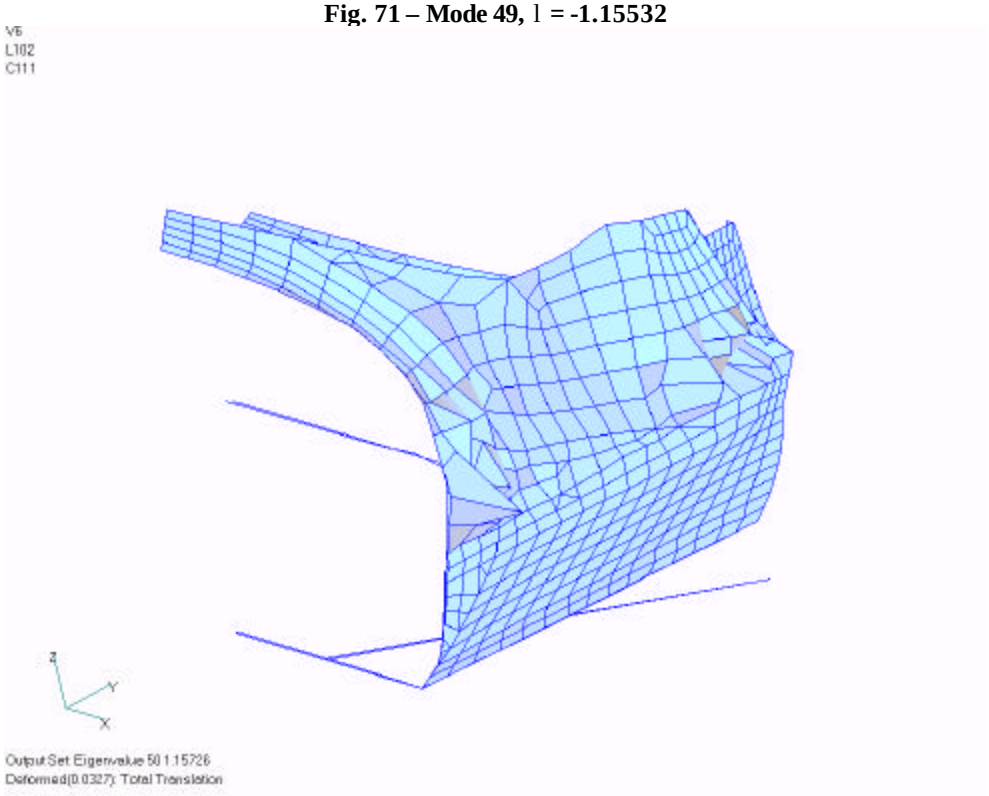

Fig. 72 – Mode 50, λ = 1.15726

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The determination of whether or not a particular mode involved the primary structure or whether it was a panel mode was based on engineering judgment after reviewing animated displays of each eigenvector. It is noted that this determination could also be based on the strain energy content of each mode. The results of this assessment are presented in Table 6 below. Note that no positive eigenvalues were computed, with magnitudes below 1.0, which involved the primary structure.

The following comments represent additional considerations based on these results. Mode 20, with a value of 0.848, is associated with deformation of the upper cabin. This mode was ignored; first because it didn't involve deformation of the primary load path, and second, because the model very conservatively under-predicted the stiffness of the upper cabin.

Table 6 – Summary of Buckling Loads

Mode	Eigenvalue	Mode Type	Mode	Eigenvalue	Mode Type
1	.0371285	panel	26	0.904509	upper cabin
2	0.46452	panel	27	-0.911465	panel
3	0.532082	panel	28	-0.927386	panel
4	0.585044	panel	29	-0.932346	panel
5	-0.654989	primary (neg)	30	-0.941208	panel
6	-0.66969	panel	31	-0.950635	panel
7	0.69686	panel	32	-0.957074	panel
8	-0.699994	panel	33	-0.96779	coupled (neg)
9	-0.70504	primary (neg)	34	0.968772	panel
10	-0.717445	panel	35	-0.97645	coupled (neg)
11	-0.735972	coupled (neg)	36	-0.994983	coupled (neg)
12	-0.744214	panel	37	-1.006317	panel
13	-0.754779	panel	38	1.016624	panel/upp cabin
14	-0.757128	panel	39	-1.029905	panel
15	-0.772303	coupled (neg)	40	-1.035548	panel
16	-0.815226	coupled (neg)	41	1.038985	upper cabin
17	-0.820155	coupled (neg)	42	-1.046654	panel
18	-0.825816	coupled (neg)	43	-1.064901	coupled
19	-0.840213	coupled (neg)	44	-1.077124	coupled
20	0.847887	upper cabin	45	-1.093502	panel
21	-0.857513	panel	46	-1.108406	coupled
22	-0.859574	coupled (neg)	47	-1.11938	coupled
23	-0.882151	coupled (neg)	48	-1.12236	coupled
24	-0.900771	panel	49	-1.15532	panel
25	-0.902561	coupled (neg)	50	1.15726	upper cabin

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One mode of particular interest is shown in Fig. 48 above. While this mode doesn't involve the reinforced area of fuselage in a major way, it nevertheless was a concern. Therefore a vertical stiffener was added at the centerline of the firewall in an effort to increase the strength needed to suppress this characteristic deformation mode.

The detail design of the composite stiffeners was defined so as to provide the same AE axial stiffness and EI bending stiffness as presented earlier in Table 4. The trapezoidal shape, shown in Fig. 73, was selected by composites experts at Wichita State University as the most desirable cross section for majority of the reinforcement stiffeners since it is easy to fabricate. Stiffeners with this shape were used to reinforce the longerons, the diagonal shear web stiffeners, and the upper diagonal engine mount stiffener. This shape is also desirable since it provides for a relatively large bond area between the reinforcement and the skin. The inner and outer laminates were both defined as symmetric laminates described by $[(\pm 45/0_3)_N/\pm 45/(0_3/\pm 45)_N]$ where N represents the number of $\pm 45/0_3$ ply groups. Two material forms are used in this laminate. Plies designated as ±45 refer to Newport NB321/3K70P Carbon Cloth oriented at 45° to the aircraft's longitudinal axis. Plies designated as 0_3 refer to a group of three plies of Newport NCT 321/G150 Unitape, which are aligned with the aircraft's longitudinal axis. The stiffeners were represented by CBAR elements, which were located at the centerline of the fuselage skin. Modulus weighted section properties, defined in Chapter 4.3.2.3 of Allen and Haisler's text [18], were employed in this analysis. This formulation is essentially the same as that presented by Vinson and Sierakowski in Ref. 25. Both take advantage of a one-dimensional form of Classical Lamination Theory [26].

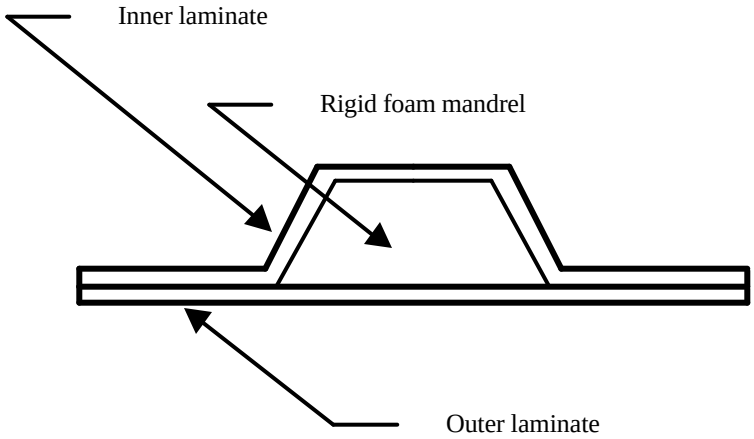

Fig. 73 – Reinforcement Cross-Section

The crippling strengths of the stiffeners were investigated since their slenderness ratios are very low, on the order of 20. The model represents a linear-elastic approach to the stiffener buckling that was predicted using NASTRAN. This model was defined using CQUAD4 plate elements, PCOMP property cards, and MAT8 orthotropic material cards. The complete NASTRAN bulk data deck is included in Appendix D of this report. One end of this model was clamped and a uniform displacement was imposed on the opposite end. P^* is evaluated from the SPC (constraint) forces computed using this kind of model. The critical buckling load is then calculated by substituting the smallest positive eigenvalue into Equation 1.

The material properties and layup schedule used in this analysis are presented in Tables 7 and 8, respectively.

Table 7 – Material Properties

Material	MID	E11	E22	n12	G12
NCT 321/G150 Unitape	102	17.767E6	1.117E6	0.321	5.50E5
NB321/3K70P Carbon Cloth	103	9.62E6	9.62E6	0.058	6.20E5

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Table 8 – Laminate Definition for the Upper Longeron Stiffener

PCOMP 111: Sides [45/0_3/45/0_3/45/0_3/45]						
	MID	**t - in**	**q - degrees**	**MID**	**t - in**	**q - degrees**
	102	0.0085	45.0	103	0.024	0.0
	102	0.0085	45.0	103	0.024	0.0
	102	0.0085	45.0	103	0.024	0.0
	102	0.0085	45.0			
PCOMP 112: Inner Surface [45/0_3/45/0_3/45/0_3/45/0_3/45/0_3/45]						
	MID	**t - in**	**q - degrees**	**MID**	**t - in**	**q - degrees**
	103	0.0085	45.0	102	0.024	0.0
	103	0.0085	45.0	102	0.024	0.0
	103	0.0085	45.0	102	0.024	0.0
	103	0.0085	45.0	102	0.024	0.0
	103	0.0085	45.0	102	0.024	0.0
	103	0.0085	45.0			
PCOMP 113: Outer Surface [45/0_3/45/0_3/45/0_3/45]						
	MID	**t - in**	**q - degrees**	**MID**	**t - in**	**q - degrees**
	103	0.0085	45.0	102	0.024	0.0
	103	0.0085	45.0	102	0.024	0.0
	103	0.0085	45.0	102	0.024	0.0
	103	0.0085	45.0			

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Representative stiffener crippling modes are presented in Figs. 74–77. The careful reader may question why mode 3 is the first mode presented. This is explained by the fact that the first two modes were dominated by end effects that are not representative of crippling behavior.

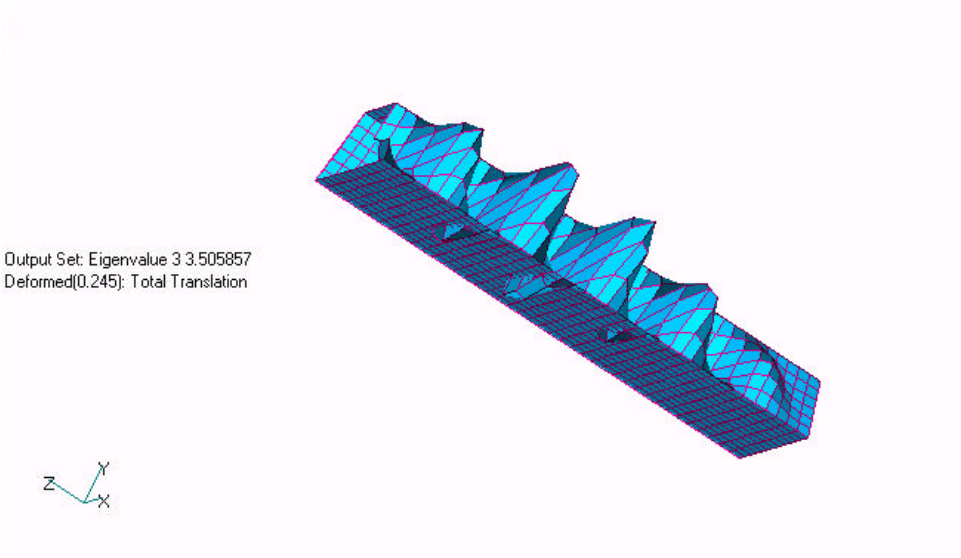

Fig. 74 – Longeron Crippling Analysis – Original Design

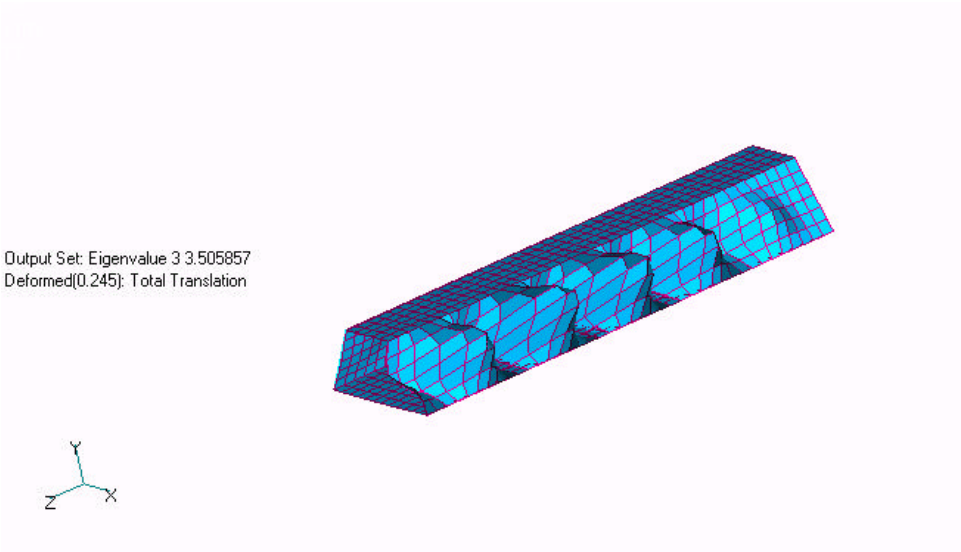

Fig. 75 – Longeron Crippling Analysis – Original Design

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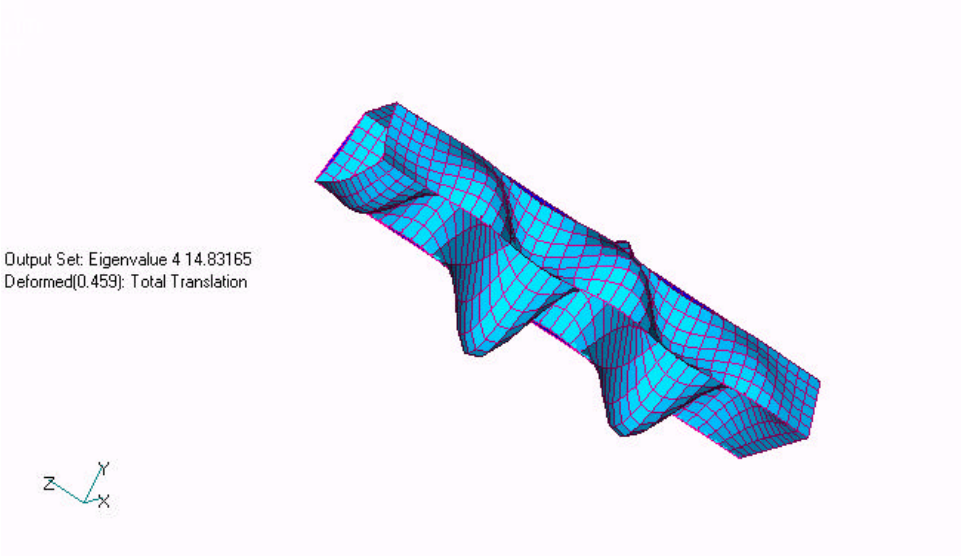

Fig. 76 – Longeron Crippling Analysis – Revised Design

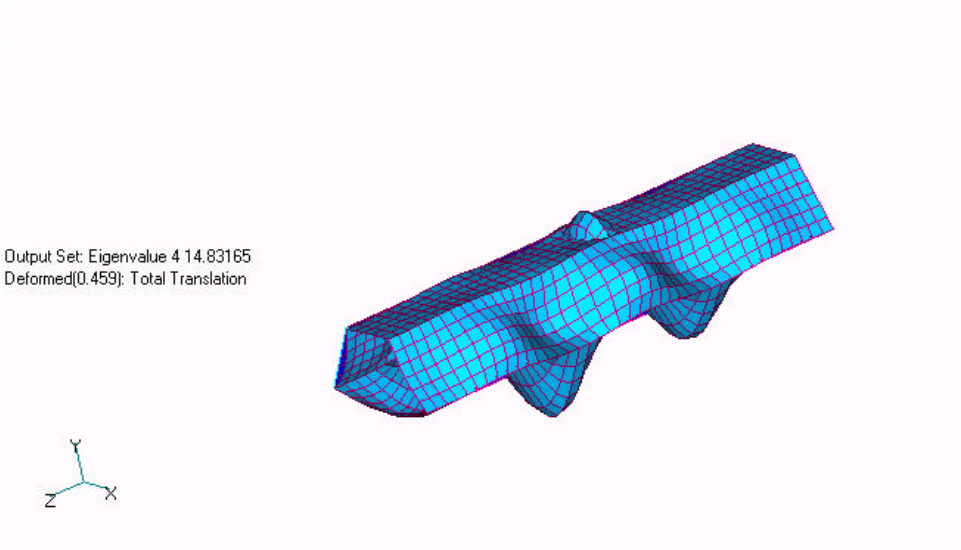

Fig. 77 – Longeron Crippling Analysis – Revised Design

These results show that the crippling strength of this member increased from 8,955 lb. to 70,172 lb. due to increasing the number of plies in the stiffener shear webs (side walls). It is also interesting to note that the eigenvector predicted for the revised design involves displacements in all of the member's faces whereas the eigenvector predicted for the original design only involved displacements of the nonparallel faces. In retrospect, it would probably be preferable if the eigenvector exhibited minimal deformation at the interface surface between the stiffener and the skin but it should be noted that these models did not include the effects of the skin, which would tend to stiffen this surface.

The design process, described above, represents the minimum-effort sizing methodology required to define the forward fuselage structure for a low-wing general aviation aircraft. It should be noted that this effort omitted the traditional static stress analysis, since buckling failures were considered to be more critical than material strength issues. The stress analysis is imbedded within the nonlinear finite element analysis, presented in the next section of this report.

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A new LS-DYNA model was created to validate the design process described above. This model was created by modifying the simple FEA model of the engine mount, engine, firewall, and airframe used to predict the firewall loads, shown in Fig. 9. These modifications included the creation of a smaller, symmetric model and the addition of the structural reinforcements described in the previous section. This model is shown in Fig. 78.

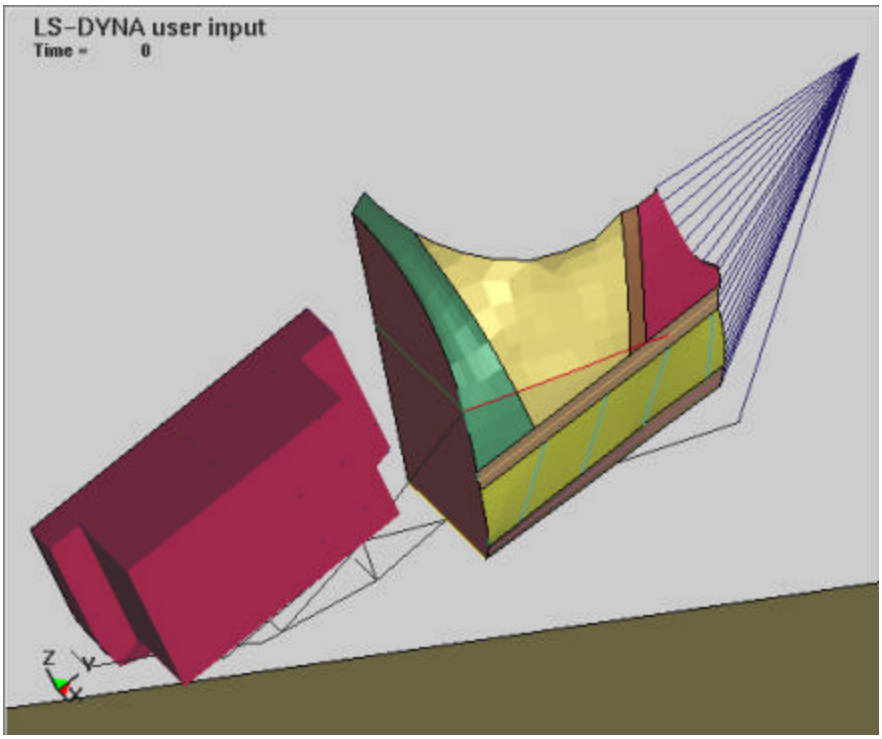

Fig. 78 – LS-DYNA Model of Engine Mount and Forward Fuselage

This model is identical to the left half of the previous LS-DYNA model forward of the firewall. The forward fuselage structure was added, including the modifications to the sidewalls. This forward fuselage structure consists of beam elements and shell elements. The beam elements were added using the section properties described in Table 4, and the shell elements were added as composite materials with layup schedules described in Table 5. The inertia properties of the rigid airframe portion of this model were defined to represent the overall inertia properties of the aircraft (reference Table 2).

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This model was also analyzed for the 30 degree impact onto a hard surface at an impact speed of 94.5 ft/sec (57 knots). The results of this analysis are illustrated by the time sequence presented in Fig. 79.

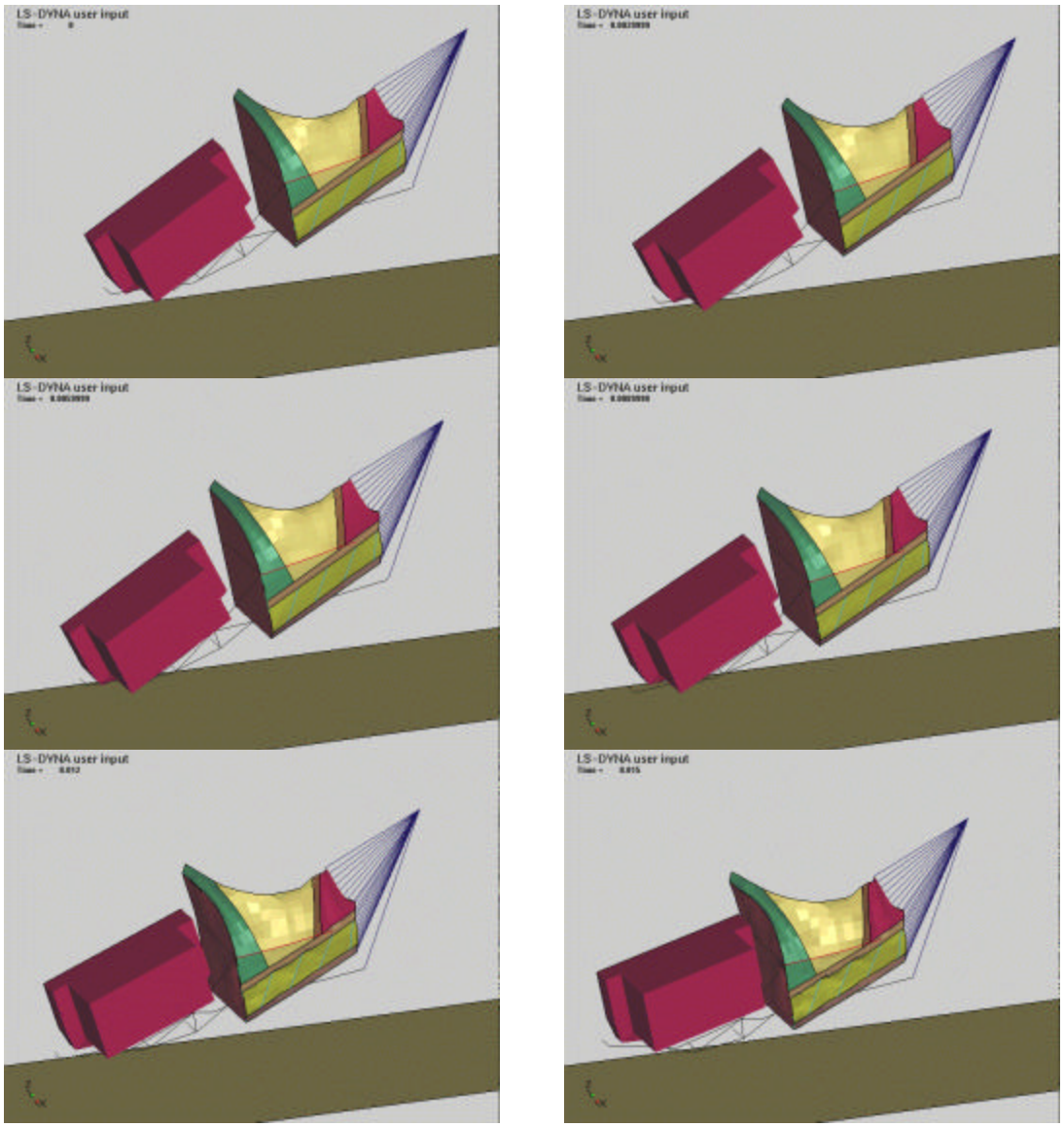

Fig. 79 – LS-DYNA Analysis Time Sequence

These results were used to verify the design recommendations developed using the NASTRAN analyses that were presented earlier in this report. The results of this analysis indicate that the added reinforcements in the forward portion of the fuselage, including the firewall, should be strong enough to maintain a survivable volume.

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The design of the energy absorbing subfloor was considered next. This required a design that specified the amount and location of foam required to attenuate the vertical accelerations at the seat track locations and in the baggage compartment. The latter consideration was motivated by the desire to protect the data acquisition system.

The FEA model of the engine mount, engine, firewall, forward fuselage, and airframe, shown in Fig. 78, was modified by adding the aft and upper fuselage structure since this was needed to design the energy absorbing subfloor. The added structure includes the belly, the windshield, the wing spar structure, some of the structure below the rear passenger seat, and portions of the aft fuselage structure. These modifications were created to accurately represent the load path between the contact surface and the occupants. The model of the forward fuselage structure is identical to the previous model. This portion of the model accurately represents the design of the composite structure modeled as accurately as possible. The remainder of the fuselage structure was modeled as composite materials, but modeled as simply as possible because details of failure mechanisms were not needed in this portion of the model. The inertia properties of the rigid airframe model were again defined to maintain the overall inertia properties of the aircraft (reference Table 2). The resulting model is shown in Fig. 80.

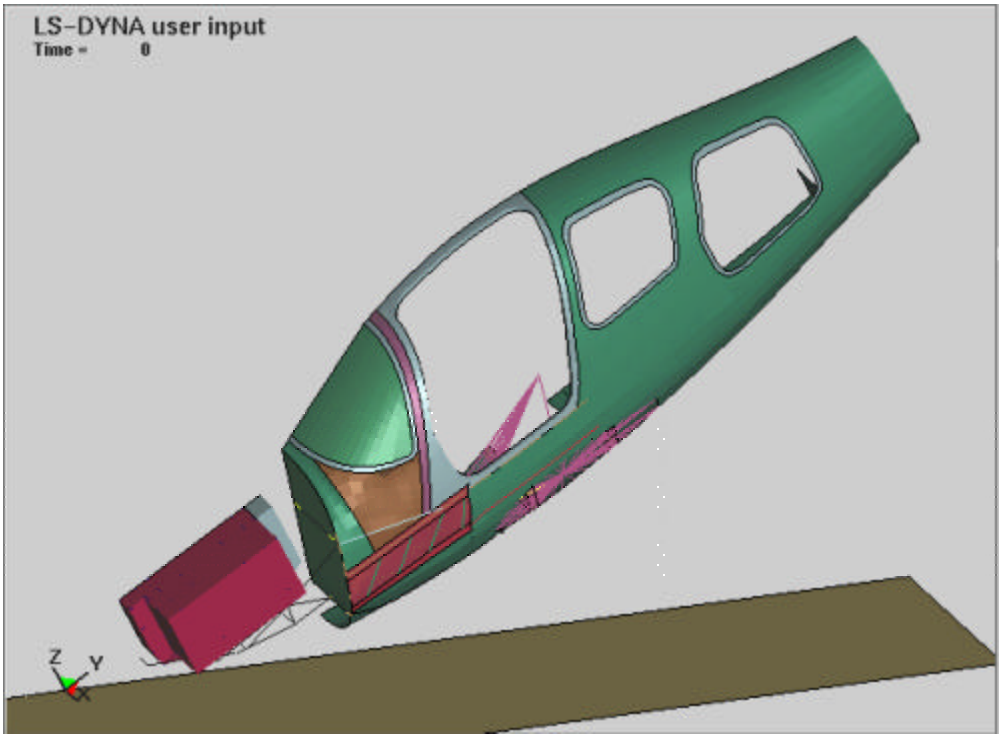

Fig. 80 – LS-DYNA Model of Aircraft

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This FEA model was used to evaluate different energy absorber (EA) subfloor designs. As stated above, the goals were to determine where to place the energy absorbing foam and to establish how much to install. A 300 psi rigid tooling foam, TC 300A, was selected because of its availability and suitability for this application. Its stress-strain properties are shown in Fig. 81.

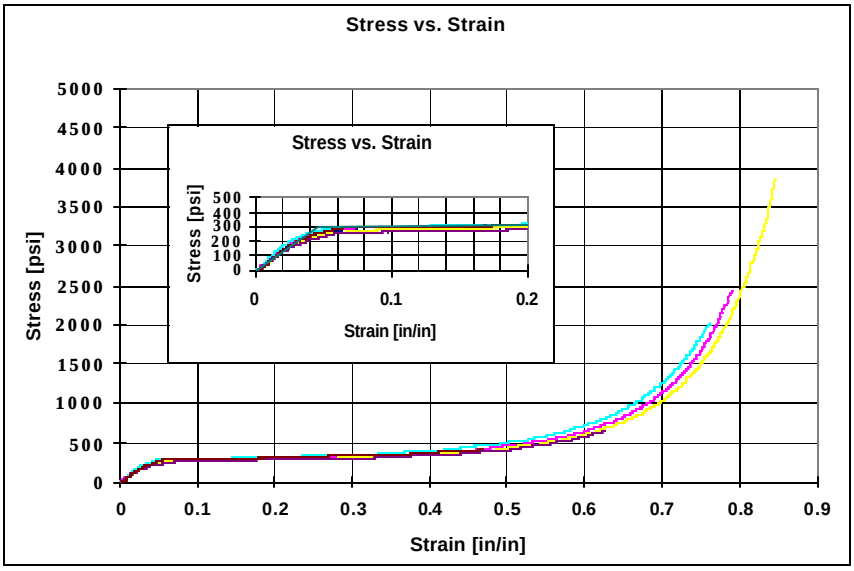

Fig. 81 – Constitutive Properties of TC 300A Foam

Several locations for the foam energy absorbers were considered. The four initial choices were based on work reported by Terry [9] and included: under the ramp at the bottom of the firewall, under the pilot and copilot seats, under the rear passenger seats, and under the baggage compartment (which is where the instrumentation is installed). These locations are illustrated in Fig. 82.

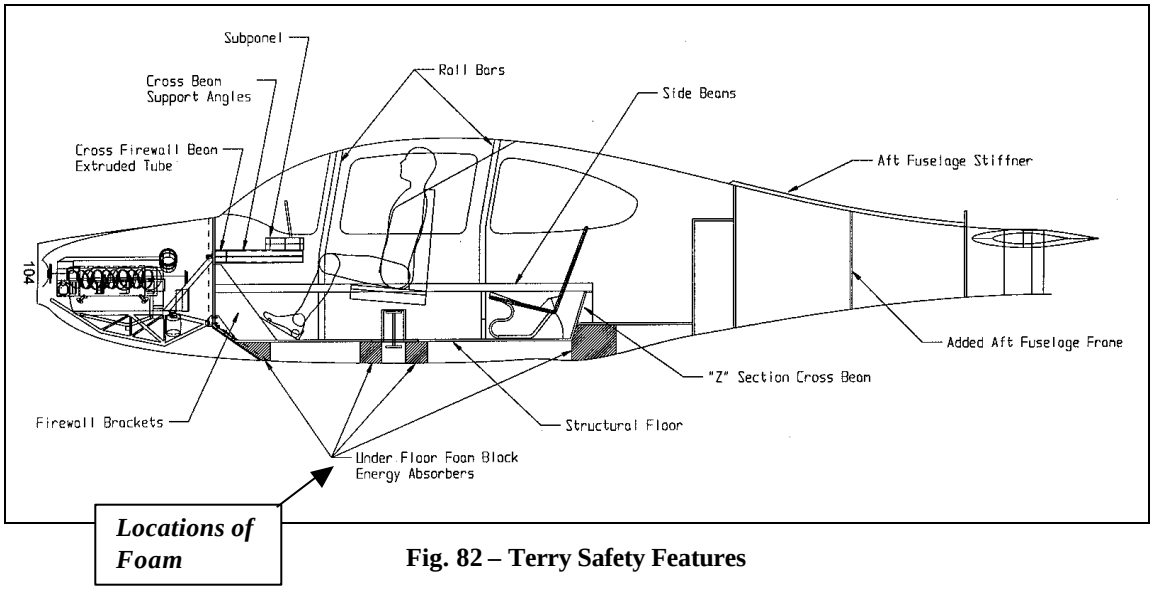

Fig. 82 – Terry Safety Features

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The foam EA's must be installed below structure that is stronger than the foam's crush strength. Installing an energy absorbing foam below structure that is weaker than the foam will, result in no energy being absorbed in the foam, probably produce a structure failure, and possibly have other undesirable consequences. Fig. 83 illustrates the candidate locations selected for the AGATE drop test article.

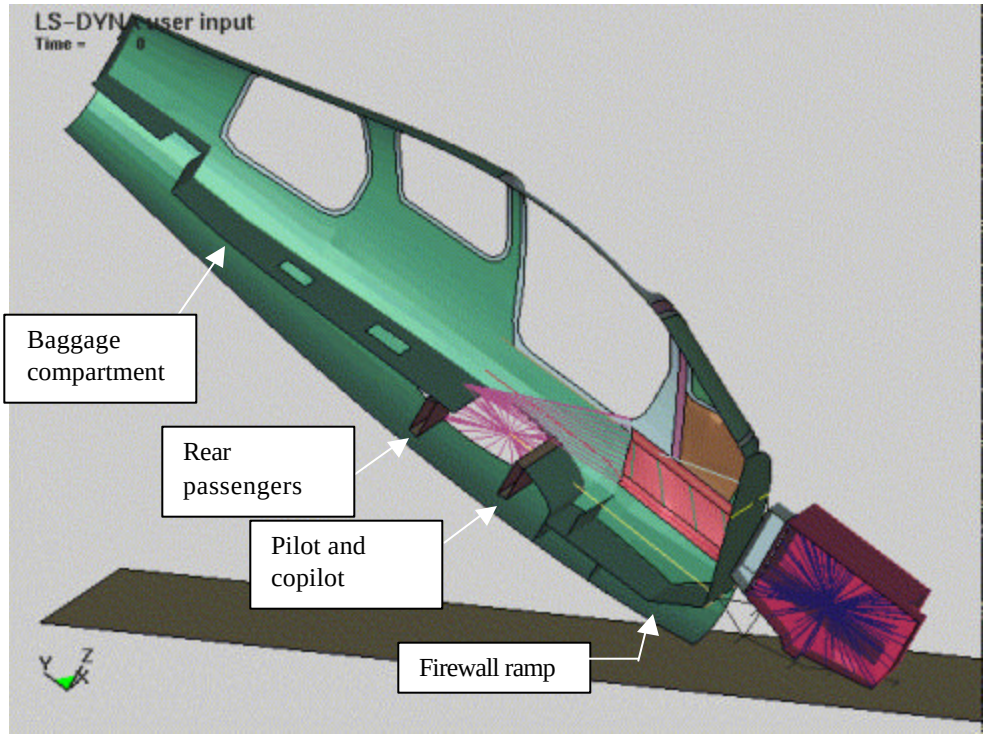

Fig. 83 – LS-DYNA Model of Aircraft – Possible EA Foam Locations

The baseline Lancair structure possessed adequate strength below the passenger and crew seats since these locations were below the lower wing spar caps. Hence, these were obvious locations for the energy absorbing foam. The forward location beneath the firewall ramp was more questionable, as was the location below the baggage compartment. While not reflected in the finite element model, a relatively heavy steel landing gear support structure is installed under the baggage compartment in the Lancair design. This structure was judged to possess adequate strength however its irregular shape motivated questions regarding the kind of crushing behavior it would produce in the foam EA's.

The foam energy absorbers were represented in the finite element model as discrete nonlinear springs whose load-deflection properties represented a particular foam block. The load-deflection curves were based on the stress-strain curves presented in Fig. 81 as well as the cross sectional area of the block and its thickness.

The installation of foam EA's, located under the ramp was evaluated first since they are closest to the impact point. The results of this analysis immediately pointed to a problem with the strength of the fuselage structure in this location. A number of EA designs, employing various spring properties and locations, were considered as possible remedies. In each case, however, the structure supporting the ramp lacked sufficient strength to resist the loads from the EA device. Surprisingly, the model predicted that fuselage structure possessed sufficient strength to resist the impact loads if no EA device was installed. Consequently, these EA's were not included in the design. It should be noted that this finding is probably a specific rather than a generic result. Therefore, each design should be analyzed to determine the best subfloor EA configuration for its particular combination of geometry, structural design, and inertia loading.

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As discussed earlier in this report, the solution of explicit finite element models, such as the ones described here, involves the time-wise integration of the governing equations. Hence, the solution is predicted starting at the point of contact between the airframe and the contact point and proceeds by following the load aft to the aircraft center of gravity. Therefore the EA springs located under the crew and passenger seats did not affect the design study for the firewall EA and were evaluated separately.

The design of the EA springs under the crew and passenger seats was supported by the model illustrated in Fig. 84. These discrete EA's were designed based on results predicted during a number of parameter studies that were performed using this model.

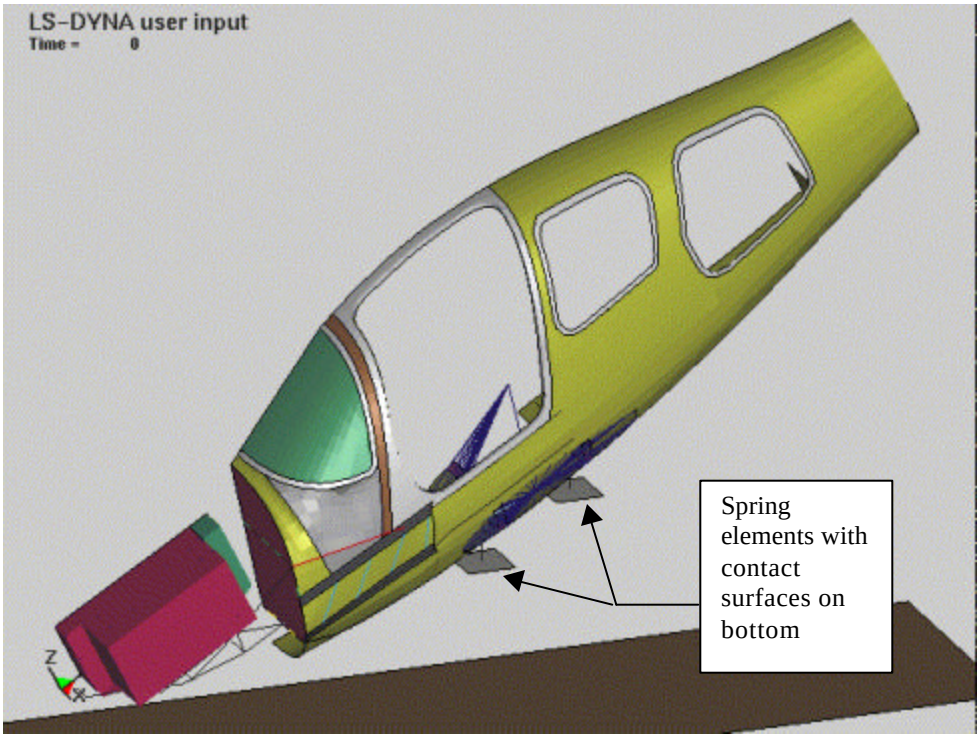

Fig. 84 – LS-DYNA Model of Aircraft – EA Foam Represented by Spring Elements

The final design specified foam blocks, each with a cross-sectional area of 144 in^2 and depth of 9 in, to be installed at the identified locations. Due to the lengthy run times for this model, EA's with the same dimensions were specified for the locations under the baggage compartment.

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Structural Modifications

The drop test article was fabricated, by modifying a Lancair Columbia 300 airframe. These modifications were performed at three locations. The structural modification to the overhead beam was fabricated in the R&D shop at the Lancair factory in Bend, Oregon. The modifications to the fuselage sidewalls were fabricated at the National Institute for Aviation Research on the Wichita State University campus. The final modifications were made in the hangar adjacent to the Impact Dynamics Test Facility at the NASA Langley Research Center in Hampton, VA.

Overhead Beam Reinforcement

The initial airframe analysis of the aircraft, performed by Simula Technologies, revealed that the overhead beam between the front and rear doorposts buckled very early in the impact. Consequently, this member was reinforced before the sidewall reinforcements were designed. This member was originally designed as a channel section. The reinforcement transformed this member into a rectangular tube.

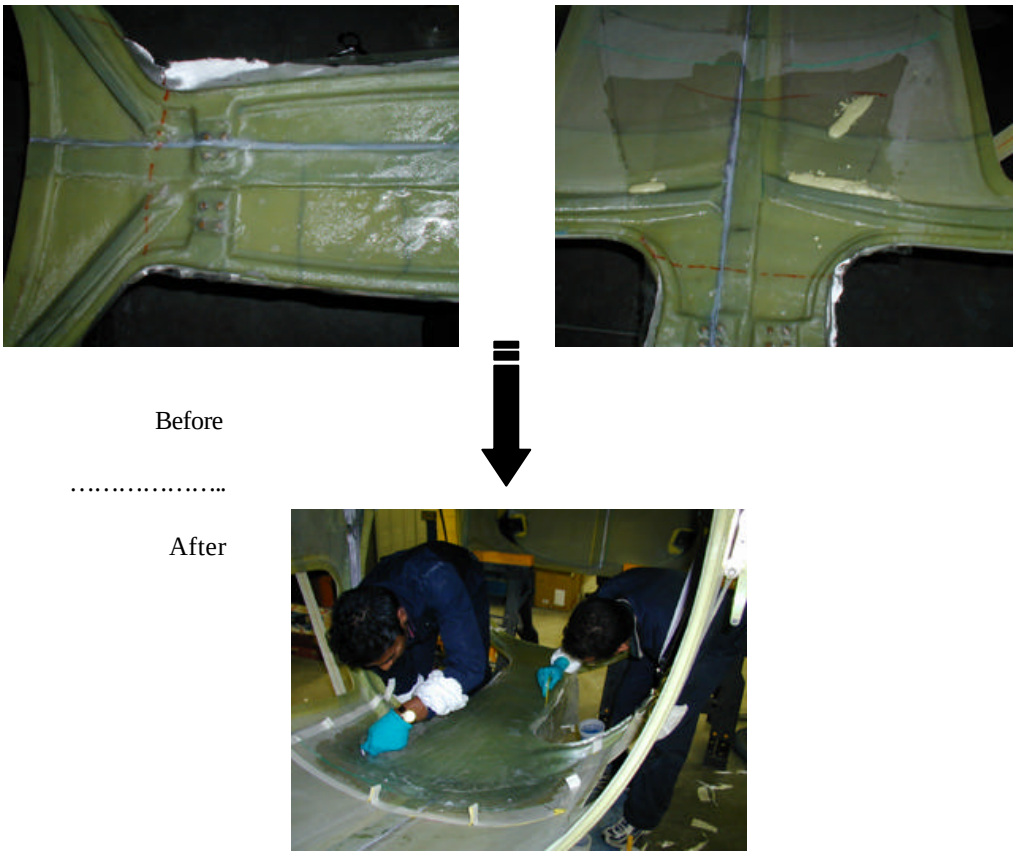

Fig. 85 – Overhead Beam Reinforcement

The layup sequence for the overhead beam reinforcement was designed to distribute the loads from the front window frame through the overhead beam and then to the top half of the tail-cone (Figure 85). The existing layup schedule of the overhead beam was repeated for the reinforcement layup with 2-inch thick pour-foam

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sandwiched in the middle as tooling. Finally, additional layers (indicated by the bold letters) were wrapped around the overhead beams to provide for improved load transfer to the aft fuselage structure.

[Layup schedule: 45/TC 300 Foam/ **45**/45/0_3/**0**/0_3/**45**/45/0_7/45_2/0/45/**45**]

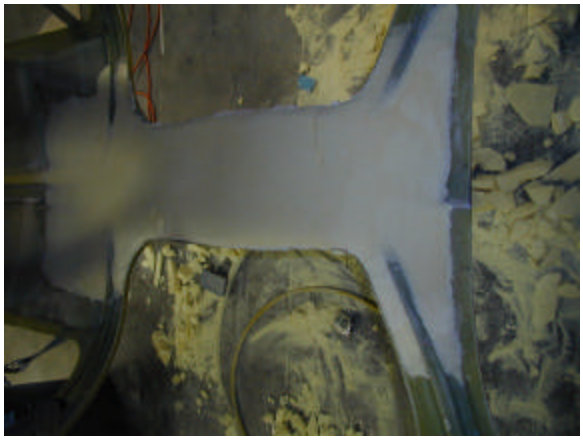

Fig. 86 – Shaped Pour-Foam for the Overhead Beam Reinforcement

The first step in the fabrication of this member was to aggressively sand the interior surface of the original overhead beam, being careful not to damage the fiberglass fibers. This surface was subsequently cleaned with acetone. It should be emphasized that surface preparation is a very important task to ensure proper bonding of the reinforcement to the overhead beam. A "water-break test" was performed to check the sanding technique. In this test, water must flow smoothly without scattering when applied to the sanded surface.

A single layer of ±45° glass fabric (7781 Satin) was placed in the structure as a wet-layup. This layer was installed to increase the bond strength between the pour-foam and the existing overhead beam. TC 300 pour-foam parts A and B (50:50 by weight) were mixed and poured over this region after the wet-layup had cured (the fuselage was upside-down during this process). Care was exercised to endure that the pour-foam was mixed well in order to achieve the desired foam density. The cured foam was shaped to a nominal 2-inch thickness using cutting tools and sanding equipment as shown in Figure 86.

The fabrication continued with the installation of the top half of the wet-layup reinforcement. This installation required a substantial amount of resin since the interior plies covered a large area. Therefore the L 285 Resin and Hardener 286 (100:40 by weight) were mixed in small batches as the layup proceeded. The assembly was vacuum bagged with breather cloths and separator films in order to absorb excess resin and trapped air. Vacuum bagging also increases the fiber volume fraction of the wet-layup. The tail-cone top adhesive lap joint was also reinforced with two layers of 4-inch wide cross-ply glass fabric (7781 Satin) that were installed as a wet-layup and then vacuum bagged.

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Firewall & Longeron Stiffeners

Since the strength of the secondary bonds between the carbon stiffeners and the original airframe was considered critical to the success of the test, extra care was taken for the surface preparation in these areas. Personnel from the Composites Laboratory at the National Institute for Aviation Research, Wichita, Kansas, were selected to perform this work since they have extensive experience fabricating and testing composite material coupons. Their knowledge, gained in preparing and testing thousands of tabbed coupons to failure over the course of the AGATE program, was judged to be key to the success of these modifications.

The first, and one of the key steps in the installation of the sidewall reinforcements was to aggressively sand the inside of the fuselage shell at the reinforcement locations. Care was taken not to damage the underlying fiberglass fibers. The water-break test was performed at each sanded location as described previously. The following photos illustrate the wet lay-up process used to fabricate the stiffeners.

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The following section of this report is presented in the form of *planning* sheets that contain a step-by-step description of the fabrication process.

Fig. 87 – Sealant Tape Installation Required for Vacuum Bag

1. Surface preparation consists of the following steps:

    a. Sand the reinforcement region and clean with acetone.
    b. Perform the 'water-break test'.
    c. Wipe and clean the surface.
    d. Prepare the sealant tape for the vacuum bag. (This allows the start of bagging immediately following the wet-layup, before the resin starts the exothermic reaction.)

The forward fuselage reinforcements were all designed using the cross section shown in Fig. 88. Their fabrication steps are summarized as:

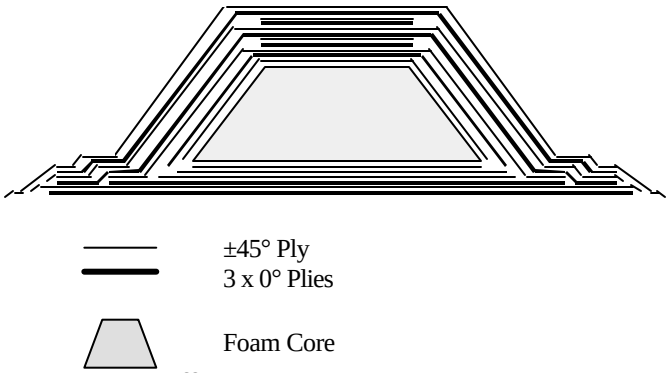

Fig. 88 – Stiffener Cross Section and Layup Schedule

2. Cut plies and foam-core:

    a. Determine the dimensions of each ply and the core. Note that the width of each ply must be designed to step down as shown in the layup schematic (Fig. 88).
    b. Cut plies required for the wet-layup.
    c. Cut and trim the foam core.
    d. Cut breather cloths, separator film and bagging material for the vacuum bag.

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3. Wet the plies with resin.

   a. Lay 3-5 plies separately on a bagging material. Start from the bottom most ply of the wet-layup and follow the layup sequence.
   b. Pour mixed resin and spread evenly using a squeegee. Care must be taken not to distort fiber alignment.

Fig. 89 – Material Wet-Out

   c. Cut each layer and roll, separately. This prevents fiber distortion, when laying-up a narrow, long layup.

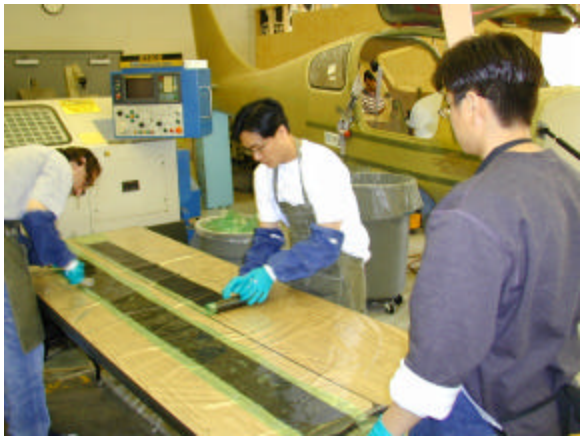

Fig. 90 – Ply Preparation

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4. Layup

   a. Start from one end and unwrap the wetted plies.
   b. Press it against the wall and squeeze and remove trapped air and wrinkles.
   c. Do not let any bridges form at places where the plies are bent.
   d. In some places, plies may have to be cut or trimmed, in order to lay them around obstacles such as the rudder pedals or instrument panel mounting brackets.

Fig. 91 – Laminate Preparation

5. Vacuum bag and cure

   a. Install separator films and breather cloths over the laminate after all of the plies had been layed up.
   b. Overlay the laminate with a vacuum bag and perform a vacuum check. (One is advised to prepare the required items for this task and have them at hand before starting the layup, so that the vacuum bag can be completed before an exothermic reaction of the resin starts.)
   c. Care must be taken to avoid bridges in the vacuum bag material.
   d. Maintain the vacuum pressure on the part during the cure cycle. (This is critical to the production of parts with a high fiber-volume fraction.)

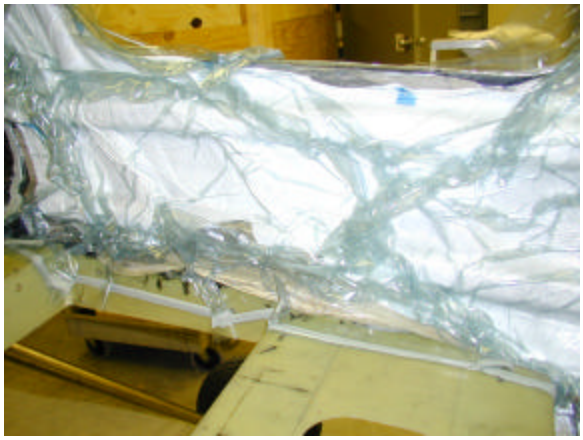

Fig. 92 – Bagged Reinforcements

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Stiffeners were installed in the forward fuselage as illustrated in Fig. 93 below.

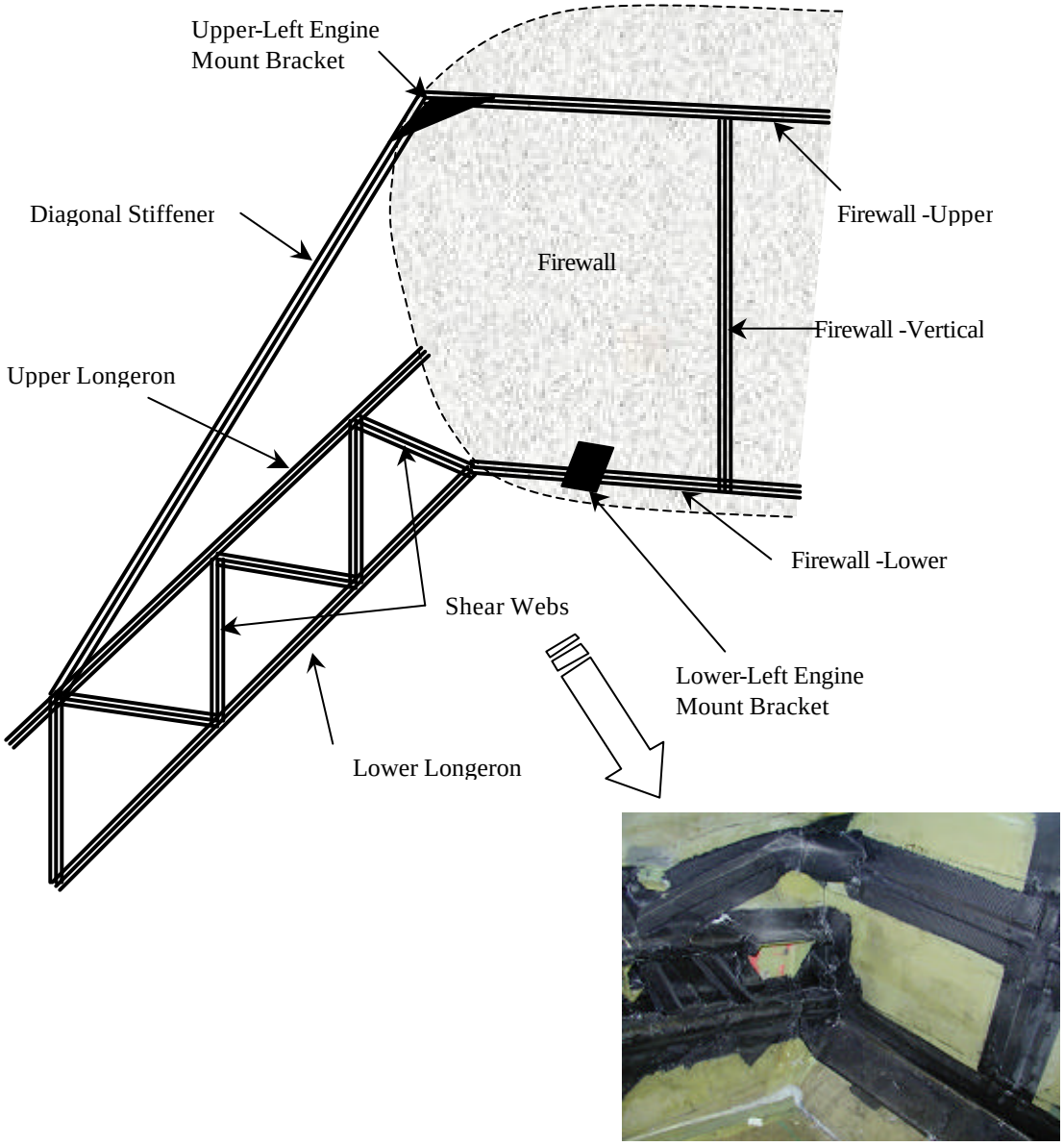

Fig. 93 – Stiffener Locations (Left Side of the Fuselage)

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The layup schedule for each of these stiffeners is summarized in Table 9.

Table 9 – Layup Sequences for the Wet-Layup of Stiffeners.

Stiffeners*	Core [a, b, c]**	Layup Sequence		
		Top	Bottom	Sides
Top Longeron	1, 2.4, 1.125	$45/[0_3/45]_5$	$45/[0_3/45]_3$	$45/[0_3/45]_3$
Bottom Longeron	1, 2.4, 1.125	$45/[0_3/45]_5$	$45/[0_3/45]_3$	$45/[0_3/45]_3$
Shear Webs	1.4, 2.25, 0.75	$45/[0_3/45]_3$	$45/[0_3/45]_2$	$45/[0_3/45]_2$
Firewall –Vertical	2, 1.9, 0.75	$45/[0_3/45]_3$	$45/[0_3/45]_2$	$45/[0_3/45]_2$
Firewall –Upper	1, 2.4, 1.125	$45/[0_3/45]_5$	$45/[0_3/45]_3$	$45/[0_3/45]_3$
Firewall -Lower	2, 2, 3***	$45/[0_3/45]_6$	$45/[0_3/45]_4$	$45/[0_3/45]_3$
Diagonal Stiffener	1, 2.4, 1.125	$45/[0_3/45]_5$	$45/[0_3/45]_5$	$45/[0_3/45]_5$

NOTE: * Refer to Fig. 93
** Refer to Fig. 94
***Trapezoid cross section

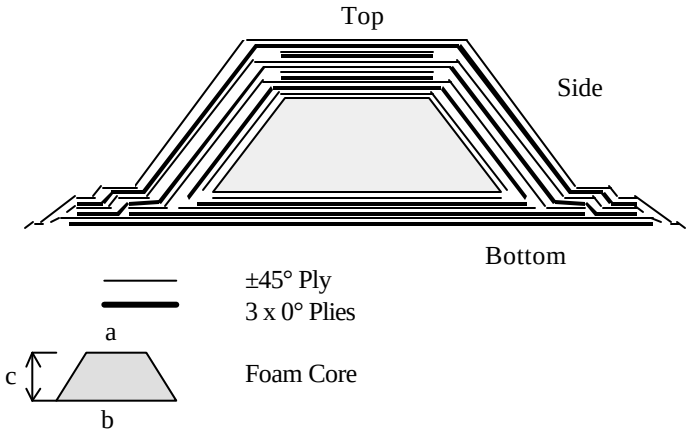

Fig. 94 – Wet-Layup Sequence.

The laminates employed in the stiffener designs did not include more than three 0° plies in a single ply group in order to avoid delamination failures between these plies and the adjacent ±45° fabric. In addition, ±45° fabric was installed at the interface between the fuselage-stiffeners to increase the inter-lamina shear strength of this bond. The 'Hat' cross-section was selected because it provides reasonable structural efficiency and because it provides a number of fabrication considerations such as accommodating contour variations at the reinforcement locations, offering proper vacuum bagging without any bridging, etc.

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As shown in Figure 95, the bag side of the wet-layup was uneven (not smooth) due to the overlapping of adjacent layups. This cannot be avoided in laminated structures. The strength degradation due to these imperfections was addressed in the structural analysis described earlier in this report.

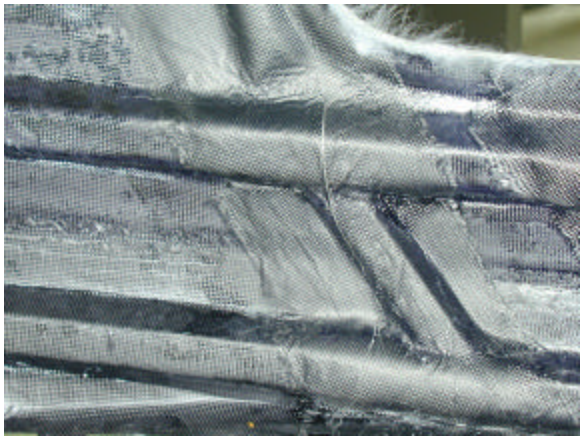

Fig. 95 – Bag Side of the Wet-Layup.

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Lower Engine Mount Reinforcement

The strength of the lower fuselage structure of the Lancair airframe is inadequate to resist the impact loads applied to the lower engine mounts. As discussed earlier, two tubular columns represented the most convenient reinforcement to transfer the impact loads from the lower firewall back to the forward region of the "saddle structure" as shown in Fig. 96. The "saddle structure" is a very strong fiberglass structure that supports the interface loads between the wing and fuselage. Furthermore, it is conveniently located near the aircraft center of gravity. Both facts support the decision to transfer the lower engine mount impact loads to this location.

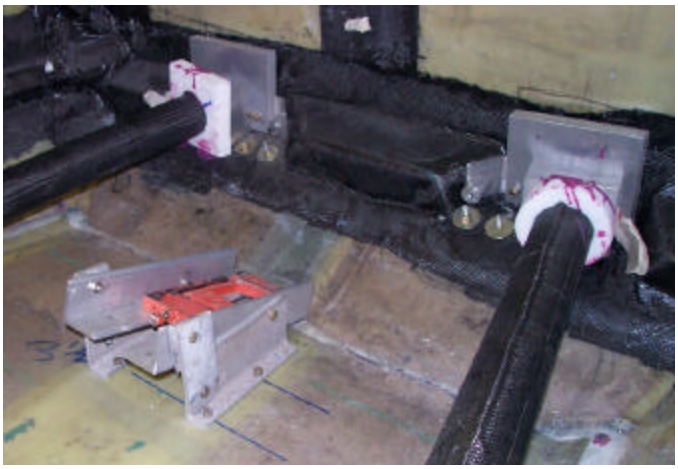

Fig. 96 – Lower Fuselage Reinforcement Tubes

Since tubes with the desired cross section could not be obtained in a timely manner, the members were fabricated by wrapping composite material around 2.4-in. diameter steel tubes with a 0.083-in. wall thickness. The reinforcement layer consisted of a $[0_{GL}/0_{GR}/(0_3/0_{GR})_2]$ laminate where

0_{GL} denotes one layer of Newport 7781 Fiberglass Cloth that is aligned with the tube,

0_{GR} denotes one layer of graphite fabric, also aligned with the tube, and

0_3 denotes three layers of unidirectional graphite tape.

The glass layer was inserted to insulate the graphite material from the steel and thus prevent galvanic corrosion between these materials. These materials were installed and processed using the same wet-layup process described earlier. The forward ends of these tubes were attached to aluminum fittings located just behind the lower engine mount attachment from inside the firewall. The aft ends were installed in aluminum fittings that beared against the front spar at a location adjacent to the saddle structure.

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The installation of the energy absorbing subfloor is illustrated in the following figures. BJB TC-300B Rigid Polyurethane Foam blocks, with a density of 12 lb/ft^3, were cut to shape and fitted inside 11-in. diameter fiberglass belly strakes as shown in Fig. 97. The ends of the foam were capped with fiberglass ribs, also shown in this figure. The gaps between the lower spar caps and fuselage skin were filled with this same foam as shown in Fig. 98.

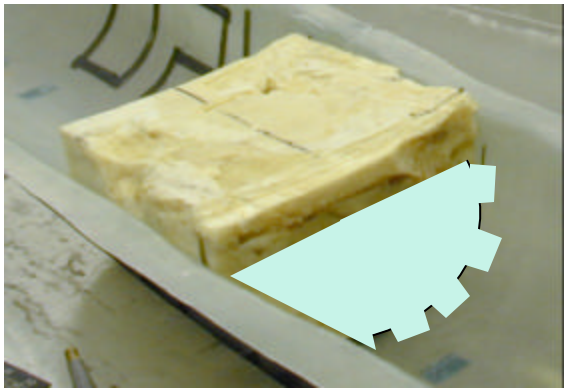

Fig. 97 – Energy Absorbing Foam Blocks

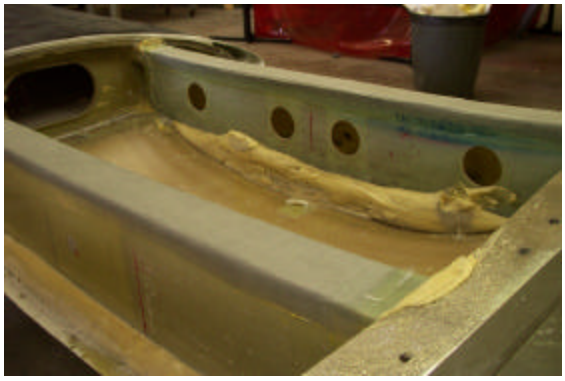

Fig. 98 – Filled Gaps Below Spar Caps

The strakes were bonded to the belly skin with Hysol EA 9309.3 two-part adhesive, which was selected for its high peel strength.

Fig. 99 – Strake Installation

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Acknowledgments

The contributions of Waruna and Nirosha Seneviratne and K.S. Raju of the National Institute of Aviation Research at Wichita State University, Mr. Nelson Seabolt of the Impact Dynamics Test Facility at NASA Langley Research Center, and Ms. Luann Schweitzer, Todd Bevin, Jay Gilbert, Clinton Crotwell, Guy George, and Don Ashenfelter of Lancair were all invaluable in completing this project.

Conclusions

This report documents the processes used to design and fabricate the composite drop test article for the AGATE crashworthiness program. The design process made extensive use of both linear and nonlinear finite element analyses in a systems approach to crashworthiness design. It is significant to note that much of the design work employed traditional linear elastic design and analysis methodologies to size the structure for the anticipated impact loads. These loads were estimated using a simple nonlinear finite element model of the engine mount and a rigid airframe. The resulting design was checked by performing a nonlinear finite element analysis of the entire structure.

The nonlinear finite element model was also employed in the design of the energy absorbing subfloor. Three observations stand out regarding this effort. The first is associated with the difficulty in modeling the friction forces that act on the structure during the contact. The second has to do with the progressive manner in which nonlinear finite element results become available. Unlike linear solutions, nonlinear solutions evolve over time and thus force the user to solve structural design problems one-by-one. They often only provide useful information for a very limited portion of the structure at the time of failure. Finally, the damage models available for composite structures do not adequately represent the residual strength of these structures after the first failure. This is especially problematic when a compressive failure is encountered before a load reversal since existing codes possess a limited capability to rationally analyze the subsequent tensile response in these cases.

Finally, this project provided a unique opportunity to challenge structural engineering tools and understanding to the limit of our understanding. A subtle, but important observation is that engineers who have extensive experience testing composite materials to failure possess an understanding about design and fabrication that cannot be attained by engineers whose experience is strictly limited to analysis and design.

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Appendix A – Crashworthy Cowl Design

Modworks designed the crashworthy cowl for the AGATE drop test article. It is illustrated in the following AUTOCAD drawing.

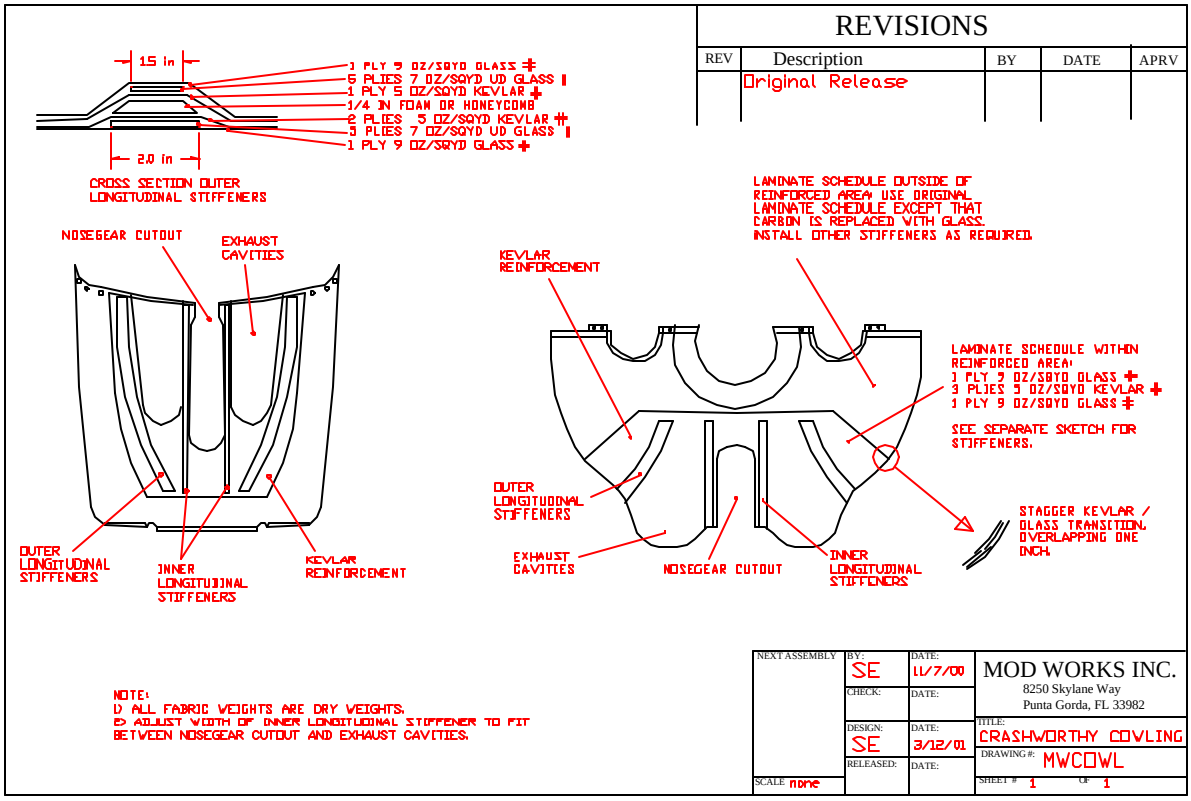

Fig. 100 – Crashworthy Cowl

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Appendix B – Crashworthy Engine Mount Design

Simula designed the crashworthy engine mount for the AGATE drop test article. It is illustrated in the following pictures.

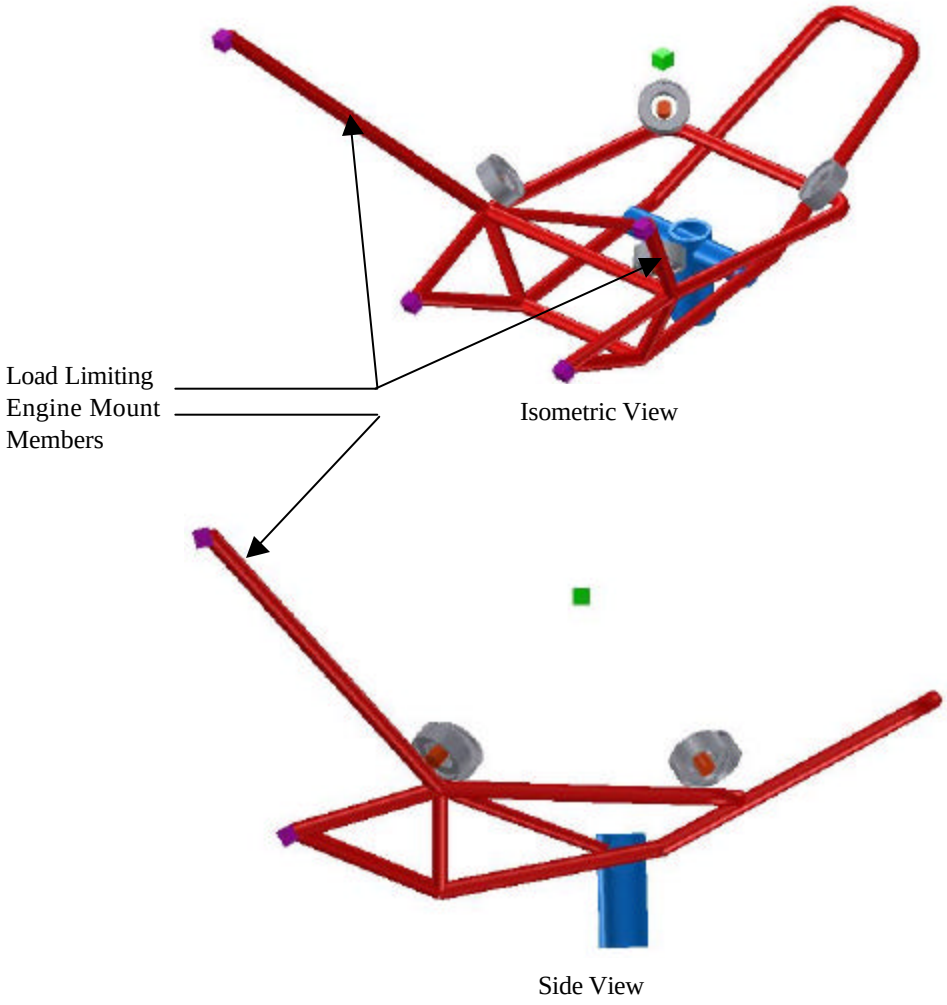

Fig. 101 – Crashworthy Engine Mount

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Appendix C – Forward Fuselage NASTRAN Bulk Data File

```
ID D:\users,FEMAP
SOL SUPERELEMENT BUCKLING
TIME 10000
CEND
MAXLINES=999999999
  ECHO = NONE
  DISPLACEMENT(PLOT) = ALL
  OLOAD(PLOT) = ALL
  SPCFORCE(PLOT) = ALL
  FORCE(PLOT,CORNER) = ALL
  STRESS(PLOT,CORNER) = ALL
  SPC  = 111
SUBCASE 1
  LOAD = 102
SUBCASE 2
  LABEL = BUCKLING CASE
  METHOD = 1
BEGIN BULK
$ ************************************************************************
$   Written by : FEMAP
$   Version    : 7.00
$   Translator : CSA/NASTRAN
$   From Model : D:\users\hooper\agate\model_4\fwd_fuse_5d.MOD
$   Date       : Sat Apr 07 11:41:08 2001
$ ************************************************************************
$
PARAM,POST,-1
EIGRL          1              2.      50       0
CORD2C         1       0      0.      0.      0.      0.      0.      1.+FEMAPC1
+FEMAPC1      1.      0.      1.
CORD2S         2       0      0.      0.      0.      0.      0.      1.+FEMAPC2
+FEMAPC2      1.      0.      1.
$ FEMAP Coordinate System 91 : firewall
CORD2R        91       0      0. 61.8832     87.      0. 89.5828 190.108+CS   2J
+CS   2J 106.764 61.8835 86.9999
$ FEMAP Load Set 102 : 50 g Hard-Surface Impact
FORCE        102     144       0      1.  16575. 36032.7 10809.8
FORCE        102     866       0      1. 14095.3 49967.3 -3091.7
$ FEMAP Constraint Set 91 : Sym BC
$ FEMAP Constraint Set 92 : Firewall Drilling dof
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SPC           111    1469     156      0.
SPC           111    1474     156      0.
SPC           111    1615  123456      0.
SPC           111    1638  123456      0.
$ FEMAP Property 1111 : fuselage laminate H
PCOMP        1111              0.           HOFF                        +
+             101  0.0098     45.     YES     101  0.0588      0.     YES+
+             101  0.0098     45.     YES     104    0.25      0.     YES+
+             101  0.0098     45.     YES     101  0.0392      0.     YES+
+             101  0.0098     45.     YES
$ FEMAP Property 1112 : Fuselage Laminate L
PCOMP        1112              0.           HOFF                        +
+             101  0.0098     45.     YES     101  0.0588      0.     YES+
+             104    0.25      0.     YES     101  0.0392      0.     YES+
+             101  0.0098     45.     YES
$ FEMAP Property 1113 : Graphite stringer (uni)
PCOMP        1113              0.           HOFF                        +
+             101  0.0098     45.     YES     101  0.0294      0.     YES+
+             102    0.12      0.     YES     101  0.0294      0.     YES+
+             101  0.0294     45.     YES     101  0.0588      0.     YES+
+             101  0.0098     45.     YES
$ FEMAP Property 1115 : aluminum firewall (N/A)
PSHELL       1115     105    0.06     105      1.     105 0.83333      0.
$ FEMAP Property 1116 : gusset
PCOMP        1116              0.           HOFF                        +
+             103  0.0104     45.     YES     103  0.0104      0.     YES+
+             103  0.0104     45.     YES     104   0.375      0.     YES+
+             103  0.0104     45.     YES     103  0.0104      0.     YES+
+             103  0.0104     45.     YES
$ FEMAP Property 1117 : firewall
PCOMP        1117              0.           HOFF                        +
+             101  0.0098     45.     YES     101  0.0392      0.     YES+
+             104    0.25      0.     YES     101  0.0392      0.     YES+
+             101  0.0098     45.     YES
$ FEMAP Property 1118 : Lwr Lat firewall beam
PBAR         1118     106 0.64375 0.19769 0.16137 0.27822      0.        +PR   V2
+PR   V2   -0.75 -0.6625    0.75 -0.6625    0.75  0.6625   -0.75  0.6625+PA   V2
```

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+PA   V2  0.5012 0.42142      0.
$ FEMAP Property 1119 : Lower Eng Mt Support Beam
PBAR        1119     107 0.63024 0.46076 0.46076 0.92138      0.        +PR   V3
+PR   V3       0.   -1.25    1.25      0.      0.    1.25   -1.25      0.+PA   V3
+PA   V3 0.53168 0.53169      0.
$ FEMAP Property 1120 : firewall tape
PROD        1120     106    0.16      0.      0.      0.
$ FEMAP Property 1121 : upper eng mt reinforcemen
PROD        1121     106    0.16      0.      0.      0.
$ FEMAP Property 1122 : Fuselage Shear Web
PCOMP       1122              0.            HOFF                      +
+            101  0.0098     45.     YES     101  0.0588      0.     YES+
+            101  0.0098     45.     YES     104    0.25      0.     YES+
+            101  0.0098     45.     YES     101  0.0392      0.     YES+
+            101  0.0098     45.     YES
$ FEMAP Property 1123 : 3 25x 1.25 x .1 hat
PBAR        1123     106   0.555  0.3623 0.128271.901E-3      0.        +PR   V7
+PR   V7  -1.625-0.52658   1.625-0.52658   0.625 0.72342  -0.625 0.72342+PA   V7
+PA   V7 0.23527  0.3133      0.
$ FEMAP Property 1124 : 3.5 x 1.5 x 1.13 x .1 hat
PBAR        1124     106   0.555 0.45791 0.10836 0.00192      0.        +PR   V8
+PR   V8   -1.75-0.49786    1.75-0.49786    0.75 0.62714   -0.75 0.62714+PA   V8
+PA   V8 0.29182 0.26578      0.
$ FEMAP Property 1125 : .75 x .75 x 2.5 x .08
PBAR        1125     106    0.38 0.144050.0275141.303E-3      0.        +PR   V9
+PR   V9   -1.25-0.27237    1.25-0.27237   0.375 0.47763  -0.375 0.47763+PA   V9
+PA   V9 0.30175 0.22563      0.
$ FEMAP Property 1126 : shear web stiffeneer
PBAR        1126     106  0.2928 0.159950.0448163.693E-4      0.        +PR   VA
+PR   VA    -1.5-0.39213     1.5-0.39213     0.5 0.60787    -0.5 0.60787+PA   VA
+PA   VA 0.25253 0.26843      0.
$ FEMAP Property 1127 : U eng mt reinforcement
PBAR        1127     106  0.3872 0.230450.0600068.591E-4      0.        +PR   VB
+PR   VB    -1.5-0.43727     1.5-0.43727   0.625 0.56273  -0.625 0.56273+PA   VB
+PA   VB 0.27694 0.27587      0.
$ FEMAP Property 1128 : Lwr Eng Mt Beam
PBAR        1128     106  0.37440.0858190.085819 0.13267      0.        +PR   VC
+PR   VC  -0.625  -0.625   0.625  -0.625   0.625   0.625  -0.625   0.625+PA   VC
+PA   VC 0.45242 0.45242      0.
$ FEMAP Property 11101 : A-Pillar, m1
PCOMP      11101              0.            HOFF                      +
+               1  0.0098     45.     YES       1  0.0098      0.     YES+
+               1  0.0098      0.     YES       1  0.0098      0.     YES+
+               1  0.0098      0.     YES       4    0.25      0.     YES+
+               1  0.0098      0.     YES       1  0.0098      0.     YES+
+               1  0.0098      0.     YES       1  0.0098      0.     YES+
+               1  0.0098     45.     YES
$ FEMAP Property 15001 : A-Pillar, m2
PCOMP      15001              0.            HOFF                      +
+               1  0.0098     45.     YES       1  0.0098      0.     YES+
+               1  0.0098      0.     YES       1  0.0098      0.     YES+
+               1  0.0098      0.     YES       1  0.0098      0.     YES+
+               1  0.0098      0.     YES       1  0.0098     45.     YES+
+               4    0.25      0.     YES       1  0.0098     45.     YES+
+               1  0.0098      0.     YES       1  0.0098      0.     YES+
+               1  0.0098      0.     YES       1  0.0098      0.     YES+
+               1  0.0098      0.     YES       1  0.0098      0.     YES+
+               1  0.0098     45.     YES
$ FEMAP Material 1 : Glass Fabric (PP)
MAT8           13350000.3350000.    0.15 350000. 350000. 350000. 1.88E-4+MT    1
+MT    1      0.      0.      0.  57000.  70000.  57000.  70000.   8430.+MA    1
+MA    1
$ FEMAP Material 4 : honeycomb core
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MAT8           4   1.E-6   1.E-6    0.33   1.E-7   2400.   4000.  4.4E-6+MT     4
+MT    4      0.      0.      0.                                          +MA     4
+MA    4
$ FEMAP Material 101 : glass fabric (WLU)
MAT8         1013350000.3350000.    0.15 350000. 350000. 350000. 2.25E-4+MT    2T
+MT   2T      0.      0.      0.  57000.  70000.  57000.  70000.   8430.+MA    2T
+MA   2T
$ FEMAP Material 102 : graphite tape (PP)
MAT8         102 1.66E+7 900000.   0.3211170000.1170000. 550000. 1.35E-4+MT    2U
+MT   2U      0.      0.      0. 212110. 124350.   5300.  24280.   9840.+MA    2U
+MA   2U
$ FEMAP Material 103 : Gr Fabric (WLU)
MAT8         1039000000.9000000.   0.058 620000. 620000. 320000. 1.55E-4+MT    2V
+MT   2V      0.      0.      0.  80960.  62310.  80960.  62310.  15000.+MA    2V
+MA   2V
$ FEMAP Material 104 : Honeycomb
MAT8         104   1.E-6   1.E-6    0.33   1.E-7   2400.   4000.  4.4E-6+MT    2W
+MT   2W      0.      0.      0.                                          +MA    2W
+MA   2W
$ FEMAP Material 105 : aluminum
MAT1         105 1.07E+74000000.    0.33 2.61E-41.255E-5     70.        +MT    2X
+MT   2X  42000.  40000.  38000.
$ FEMAP Material 106 : graphite tape (WLU)
MAT1         106  1.6E+7           0.321  1.5E-4      0.      0.        +MT    2Y
+MT   2Y 212110. 124350.   9840.
$ FEMAP Material 107 : AISI 4340 Steel
MAT1         107  2.9E+7  1.1E+7    0.32 7.35E-4  6.6E-6     70.        +MT    2Z
+MT   2Z 215000. 240000. 156000.
MAT4         1074.861E-4  0.0284
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ENDDATA
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Appendix D – Longeron Reinforcement NASTRAN Bulk Data File

```
ID D:\users,FEMAP
SOL SUPERELEMENT BUCKLING
TIME 10000
CEND
MAXLINES=999999999
  ECHO = NONE
  DISPLACEMENT(PLOT) = ALL
  OLOAD(PLOT) = ALL
  SPCFORCE(PLOT) = ALL
  FORCE(PLOT,CORNER) = ALL
  STRESS(PLOT,CORNER) = ALL
  SPC  = 1
SUBCASE 1
  LOAD = 100
SUBCASE 2
  LABEL = BUCKLING CASE
  METHOD = 1
BEGIN BULK
$ ************************************************************************
$   Written by : FEMAP
$   Version    : 7.00
$   Translator : CSA/NASTRAN
$   From Model : D:\users\hooper\agate\s1123d.MOD
$   Date       : Tue Apr 10 18:31:08 2001
$ ************************************************************************
$
PARAM,POST,-1
EIGRL          1     20.      1.       7       0
CORD2C         1       0      0.      0.      0.      0.      0.      1.+FEMAPC1
+FEMAPC1      1.      0.      1.
CORD2S         2       0      0.      0.      0.      0.      0.      1.+FEMAPC2
+FEMAPC2      1.      0.      1.
$ FEMAP Coordinate System 5 : Untitled
CORD2R         5       0  1.1808   0.106      0.  1.1808   0.106      1.+CS    5
+CS    5 2.04279 0.61293      0.
$ FEMAP Coordinate System 6 : Untitled
CORD2R         6       0 -1.1808   0.106      0. -1.1808   0.106      1.+CS    6
+CS    6-0.31881-0.40093      0.
$ FEMAP Load Set 100 : axial compression
SPCD         100    5331       3   -0.01
SPCD         100    5332       3   -0.01
SPCD         100    5334       3   -0.01
SPCD         100    5335       3   -0.01
SPCD         100    5579       3   -0.01
SPCD         100    5824       3   -0.01
SPCD         100    5825       3   -0.01
SPCD         100    5826       3   -0.01
SPCD         100    5827       3   -0.01
SPCD         100    5828       3   -0.01
SPCD         100    5829       3   -0.01
SPCD         100    6110       3   -0.01
SPCD         100    6111       3   -0.01
SPCD         100    6112       3   -0.01
SPCD         100    6113       3   -0.01
SPCD         100    6114       3   -0.01
SPCD         100    6115       3   -0.01
SPCD         100    6116       3   -0.01
SPCD         100    6404       3   -0.01
SPCD         100    6405       3   -0.01
```

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```
SPCD          100    6406       3   -0.01
SPCD          100    6407       3   -0.01
SPCD          100    6408       3   -0.01
SPCD          100    6409       3   -0.01
SPCD          100    6410       3   -0.01
SPCD          100    6411       3   -0.01
SPCD          100    6412       3   -0.01
SPCD          100    6413       3   -0.01
SPCD          100    6414       3   -0.01
SPC1,1,3,5331,5332,5334,5335,5579
SPC1,1,3,5824,THRU,5829
SPC1,1,3,6110,THRU,6116
SPC1,1,3,6404,THRU,6414
$ FEMAP Constraint Set 1 : drilling dof
SPC             1    5286  123456      0.
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$ FEMAP Property 111 : Sides
PCOMP           111              0.                                      +
+               102  0.0085     45.     YES     103   0.024      0.     YES+
+               102  0.0085     45.     YES     103   0.024      0.     YES+
+               102  0.0085     45.     YES     103   0.024      0.     YES+
+               102  0.0085     45.     YES
$ FEMAP Property 112 : top
PCOMP           112              0.                                      +
+               103  0.0085     45.     YES     102   0.024      0.     YES+
+               103  0.0085     45.     YES     102   0.024      0.     YES+
+               103  0.0085     45.     YES     102   0.024      0.     YES+
+               103  0.0085     45.     YES     102   0.024      0.     YES+
+               103  0.0085     45.     YES     102   0.024      0.     YES+
+               103  0.0085     45.     YES
$ FEMAP Property 113 : bottom
PCOMP           113              0.                                      +
+               103  0.0085     45.     YES     102   0.024      0.     YES+
+               103  0.0085     45.     YES     102   0.024      0.     YES+
+               103  0.0085     45.     YES     102   0.024      0.     YES+
+               103  0.0085     45.     YES
$ FEMAP Material 101 : E-Glass Cloth (wlu)
MAT8            1014190000.4190000.   0.138 610000.      0.      0.      0.+MT   2T
+MT   2T       0.      0.      0.  50850.  62610.  50850.  62610.  15280.+MA   2T
+MA   2T
$ FEMAP Material 102 : Gr Tape (wlu)
MAT8            1021.776E+71170000.   0.321 550000.      0.      0.      0.+MT   2U
+MT   2U       0.      0.      0. 212110. 124350.   5300.  24280.  15770.+MA   2U
+MA   2U
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$ FEMAP Material 103 : Carbon Cloth (wlu)
MAT8         1039620000.9620000.   0.058 620000.      0.      0.      0.+MT   2V
+MT   2V      0.      0.      0.  71960.  55380.  71960.  55380.  13340.+MA   2V
+MA   2V
GRID         5286       0 0.31875  1.2105      0.       0
GRID         5287       0 0.10625  1.2105      0.       0
GRID         5288       0-0.10625  1.2105      0.       0
GRID         5292       0-0.53125  1.2105     0.4       0
GRID         5299       0-0.53125  1.2105     1.8       0
GRID         5300       0-0.53125  1.2105      2.       0
GRID         5301       0-0.53125  1.2105     2.2       0
GRID         5302       0-0.53125  1.2105     2.4       0
GRID         5305       0-0.53125  1.2105      3.       0
GRID         5307       0-0.53125  1.2105     3.4       0
GRID         5308       0-0.53125  1.2105     3.6       0
GRID         5314       0-0.53125  1.2105     4.8       0
GRID         5315       0-0.53125  1.2105      5.       0
GRID         5316       0-0.53125  1.2105     5.2       0
GRID         5319       0-0.53125  1.2105     5.8       0
GRID         5321       0-0.53125  1.2105     6.2       0
GRID         5327       0-0.53125  1.2105     7.4       0
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GRID         5331       0-0.31875  1.2105      8.       0
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GRID        6718       0   0.984   0.106     4.8       0
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