Automated Analysis and Failure Load Prediction of Bolted Composite Joints

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Automated analysis of bolted composite joints is essential to the design and analysis of modern aerospace vehicles. Recently, methods for coupling FEA to the bolted joint analysis code, BJSFM, have been incorporated into the HyperSizer® Software. Coupling between the FEM and the BJSFM analysis code permits analysis and sizing optimization of bolted joint configurations using the same FEM mesh. Presented in this paper is the bolted joint analysis of the NASA Composite Crew Module (CCM). Using this structure, a robust process is described for automatically extracting fastener loads for multiple load cases and computing bypass loads for the master FEM.

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1 Introduction

The lack of an automated approach to joint analysis and design is a shortcoming in the composites industry. This paper presents a robust process for coupling between FEA and a bolted joint analysis code, BJSFM. Automated coupling between the FEM and joint analysis codes allows the stress engineer to perform trade studies between bolted joint configurations using the same FEM mesh. In current practice for bolted joint analysis, a finite element model is required where shell elements (e.g. Nastran CQUAD4) are used to model the composite skins that are to be joined and one-dimensional spring elements (e.g. Nastran CBUSH elements) are modeled to represent fasteners/bolts. The computed CBUSH element forces are read from the FEA solution and manually entered directly into the BJSFM code. This paper presents a process for automatically extracting the fastener loads, eliminating the time-consuming process of manually pulling loads from a global finite element model during bolted joint analysis. Several analysis steps are automated in this process such as the handling of multiple load cases, computing the load angle and calculating the bypass loads around the fastener, etc.

This paper describes the analysis process performed by Collier Research, as a parallel effort to the NASA NESC CCM team, to quantify fastener margins of safety using the Composite Crew Module master FEM. The CCM test article is ideal for an automated composite bolted joint analysis because there are over 500 load bearing fasteners connecting the metallic fittings to the composite pressure shell, see Figure 1. Using HyperSizer, all joints are analyzed quickly to identify fasteners with low margins of safety and critical fittings are identified at the gusset and main parachute fittings.

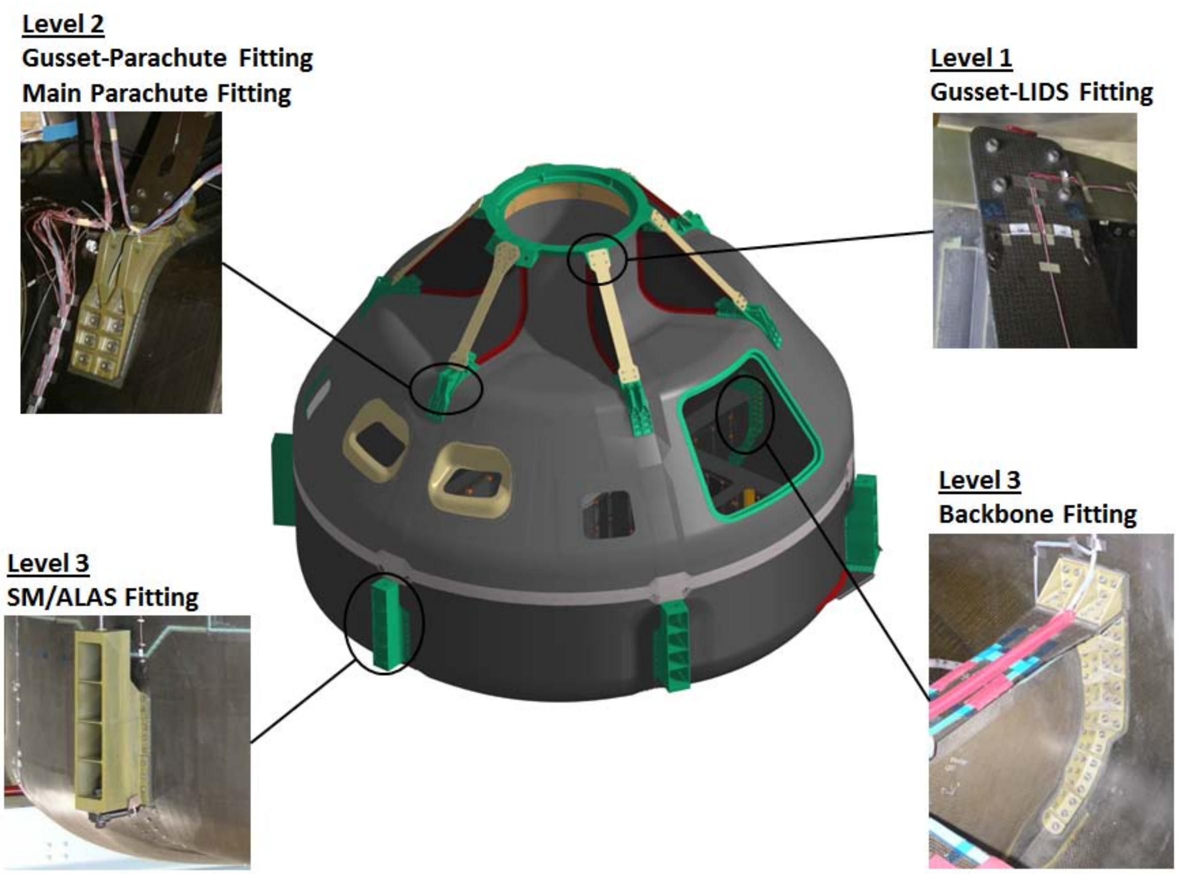

Fig. 1 - On the CCM test article, metallic bolted fittings are required in areas of high load introduction and are designed to prevent metallic yielding during testing.

1.1 CCM Master Model

A coarse meshed loads model, such as the master FEM illustrated in Figure 2, can accurately compute internal running loads around design details such as bolted attachments. Once the internal loads are properly computed, the bolted joint margins of safety are quantified for the entire CCM.

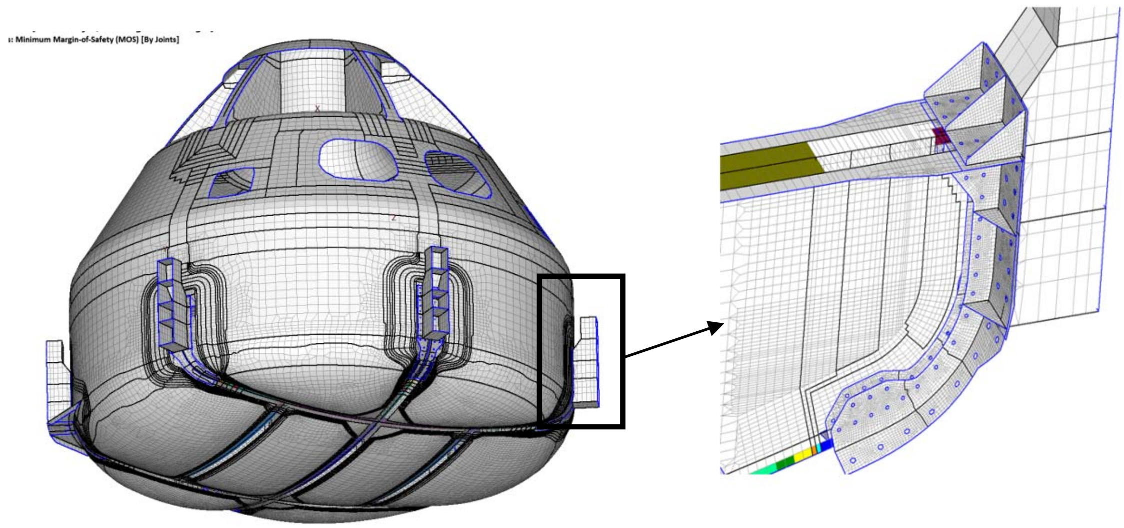

Fig. 2 - (left) The CCM master model used for internal loads includes design details such as bolted attachments, composite ply drops and windows. (right) Modeling details around backbone fitting attachment. For all fittings, the master FEM is used to compute the internal load distributions around the fasteners.

1.2 Bolted Attachment Summary

In general, bolted joints are used at locations of high concentrated load introduction. There are three primary locations of bolted attachments on the CCM which are identified as level 1-3, see Table 1. Additionally, six identical fittings are required to align with the attachments to the service module. On the test article there are 526 load-carrying fasteners requiring bolted joint analysis.

Table 1 - CCM fitting names, location and number of fasteners, see Fig. 1

Fitting Name	Level	Number of Fasteners
Gusset-LIDS	1	26
Gusset-Parachute	2	24
Main Parachute	2	84
SM/ALAS	3	192
Backbone	3	200

The Level 1 fittings are located on the upper structural assembly at the tunnel opening. The Gusset-LIDS (Low Impact Docking System) fitting is a single shear fitting used as a closeout of upper pressure shell. The gusset-LIDS ring connection transfers LIDS ring loads, such as TLI (trans-lunar insertion), into the shell structure. These fittings carry significant load during the drogue pull and the main parachute pull test cases.

Level 2 fittings are located on the upper structural assembly. The gusset-parachute fittings transfer load from the six gusset's webs to the upper pressure shell. The main parachute fittings transfer loads from the main parachute lines into the shell structure during reentry.

Level 3 fittings are located on the lower pressure shell. The SM/ALAS fittings have an upper connection to the Alternate Launch Abort System (ALAS) and a lower connection at the service module (SM). Significant load is carried in this joint during the launch abort load case. The backbone attachment fittings transfer load between the backbone attached to the lobed floor and the lower pressure shell.

1.3 CCM Test Load Cases

CCM was designed to be a test article. A free body diagram is illustrated in Figure 3, to summarize the force acting on the CCM during the primary test load cases.

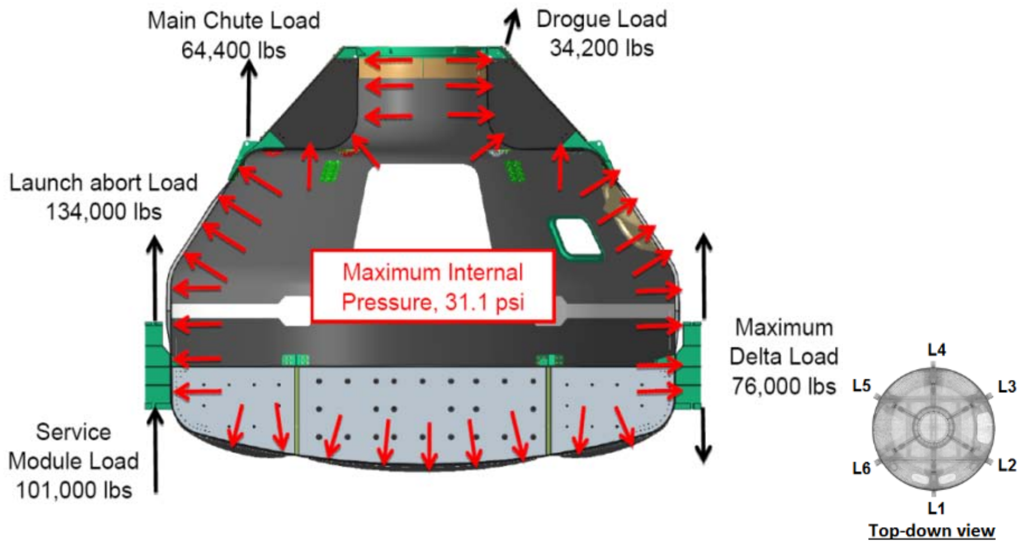

Fig. 3 - Free body summarizing CCM test load cases.

Table 2 - Test load cases, load factors and brief description [1]

Test Load Case	Load Factor		Limit Load Description
	Limit	Ultimate	
9602	0.5	1.0	214 KPa (31.1 psi) Internal Pressure
9921	0.714	1.0	286 KN (64.4 kip) Main Parachute Pull (L4 Fitting)
9302	0.714	1.0	311 KN (70 kip) Pull on SM/ALAS (L4 Fitting) with 150 KPa (21.77psi) Pressure
9917	0.714	1.0	152 KN (34.2 kip) Pull on Drogue Test Fitting (L1 Fitting)

One of the most critical load cases on the CCM fasteners is internal pressure. The CCM is designed to dock with the International Space Station (ISS). At this service condition, the pressure delta is 107.2 KPa (15.55 psi). For all pressure load cases, a 2.0 safety factor is required which results in an ultimate internal pressure of 214 KPa (31.1 psi). Test load case 9602 simulates the maximum internal pressure, see Table 2.

The drogue chutes deploy at 7620m (25,000 feet). The initial drogue pull force is reacted by the L1 gusset-LIDS fitting and the gusset-parachute fitting simultaneously. The drogue pull load case includes the internal pressure corresponding to the altitude. The main parachutes deploy at 1524m (5,000 feet). For the static test, it is assumed that the entire parachute force is applied to the L4 main parachute fitting and includes the internal pressure delta corresponding to 1524m (5,000 feet). For the drogue pull and main parachute pull load cases, identical cases without pressure were found to be less critical and were removed from the test matrix.

2 Analysis Input

2.1 Pristine Lamina Properties

Extensive material data for Composite Pre-preg IM7/977-2 tape and 4-harness fabric is available in published literature. Damaged material properties are used for the design of the vehicle and pristine properties are used for failure load prediction during the test. The properties used for this CCM bolted joint analysis are listed in Table 3.

Table 3 - Material properties used for design and failure load prediction. [4, 7, 8, 10]

IM7 4HS Fabric Material Properties	units	Damage Allowable Design Properties	Pristine Typical Test Prediction
Compressive Stiffness (Ec1=Ec2)	GPa (Msi)	69 (10)	69 (10)
Tensile Stiffness (Et1=Et2)	GPa (Msi)	69 (10)	69 (10)
Compression Strain Allowable Pre-cured	uin/in	4000	8500
Compression Strain Allowable Co-cured	uin/in	4000	7000
Tension Strain Allowable	uin/in	6000	9000

2.2 Bearing Stress Allowable

Attempts have been made to determine the bearing strength of composite material systems. However it is difficult to identify a critical bearing load due to the lack of definable failure criterion. Significant damage may result from very low loads and the damage increases with increasing loads, however, there may be no definable transition in the stress-strain plot. In this case, it is necessary to identify some limit for the amount of damage that makes the part unfit for service. Figure 4 defines the IM7/977-2 bearing allowables as a function of percent 45 degree fibers.

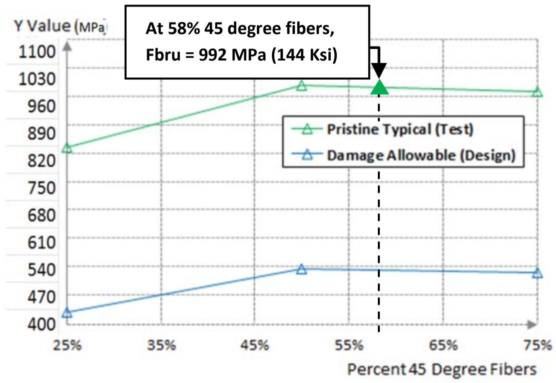

Fig. 4 - Design and test critical bearing stress with varying percent 45 degree fibers [7, 8].

2.3 Bolted Joint Analysis

The intensity of bearing force between a fastener and a laminate is not constant, but varies from zero at the edge to a maximum value at the center. Common practice is to assume the bearing force is uniformly distributed over the projected area of the fastener hole. Once the bearing load is determined, two approaches can be used to determine the bolted joint margins of safety. The first approach is to compare the bearing stress value to the composite material bearing allowable as listed in Figure 4. The applied bearing stress is determined from the bearing force, the hole diameter and laminate thickness, see Figure 5.

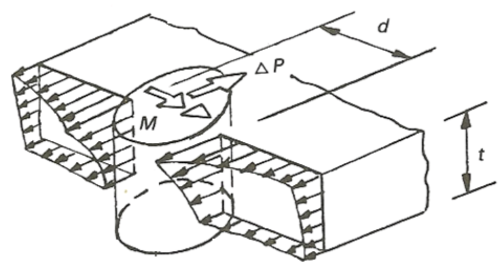

Fig. 5 - Laminate bearing analysis compares applied stress (ΔP/dt) to critical stress [9]

The second approach is to use the Air Force analysis software, BJSFM, as integrated into HyperSizer. BJSFM is a well-established computational method for analyzing a hole in a composite laminate to general membrane loading

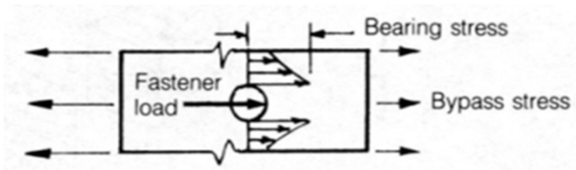

Fig. 6 - Bearing by-pass computed from the net result of bolt force and far field loading [9].

fields (Nx, Ny, Nxy) with or without bolt-bearing loads, as illustrated in Figure 6. The program operates by computing the stress/strain field at evenly spaced angular increments in evenly spaced concentric rings around a hole, see in Figure 7. This approach considers the angle of the bolt-bearing load, the effect of biaxial far field loading, and computes failure at the characteristic distance using traditional ply-based failure theories such as max strain, max stress, Tsai-Hill, Tsai-Wu, and Hoffman to determine margins of safety, see Figure 8.

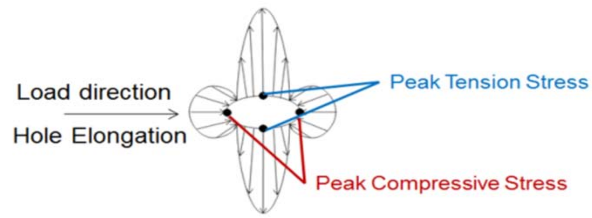

Fig. 7 - Computation of stress/strain field around the circumference of a composite laminate. hole.

BJSFM computes the same stress/strain distribution as a finely meshed shell FEM, however this approach is much faster and more robust because it is not a function of mesh fineness. Bolt analyses are semi-empirical in that they all require experimental testing to establish the parameters to calibrate stress predictions with tests. So the issue becomes predicting failure load rather than predicting laminate stress/strain. To resolve the unknown relationship between failure and stress gradients, the practical approach is to determine a characteristic distance**.** The characteristic distance is the distance away from the free edge/bearing surface to apply composite failure strength criteria, see Figure 9. The characteristic distance is a fundamental data entry passed from HyperSizer to the bolt hole analysis routine. For composites, the characteristic distance is primarily a function of the lamina material selection and the sign of the bypass load.

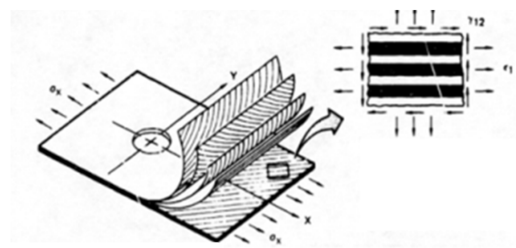

Fig. 8 - Computation of lamina strength margins of safety for each ply [9].

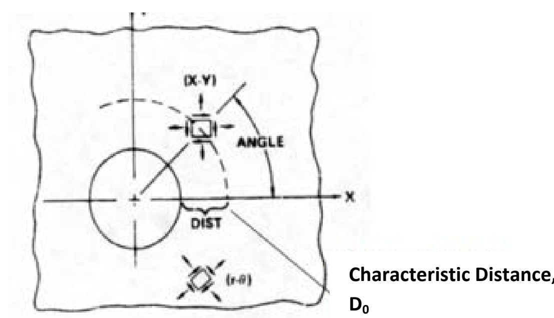

Fig. 9 - The characteristic distance is measured radially outward from edge of the hole[9]..

The MIL-HDBK-17 method for determining the characteristic distance is illustrated in Figure 10. In this method, the characteristic distance is calibrated using open hole strain allowable properties. MIL-HDBK-17 suggests a baseline characteristic distance of 0.016 for both tension and compression bypass loads. However, since the characteristic distance is a function of material selection, a unique characteristic distance is required for each lamina material definition. To accomplish this, a quasi-isotropic laminate with a 6.35mm (0.25in) hole is defined with tension and compression axial loads (Nx). Then, the characteristic distances are selected (D0t, D0c) to match the margins of safety for (1) the BJSFM analysis with bypass load only and (2) the open hole strain composite strength analysis. For the CCM, the calibration to damaged strain allowables yields a D0t = 0.304mm (0.012in) and a D0c = 0.203mm (0.008in), which are used

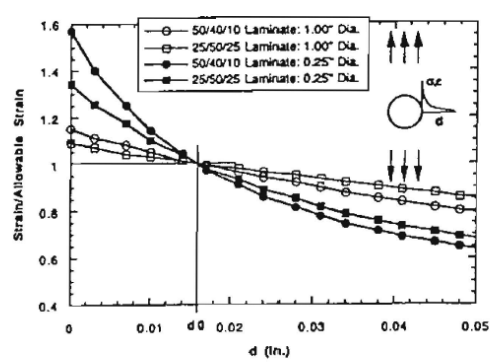

Fig. 10 - Calibration of characteristic distances to strain allowables, D0 = 0.406mm (0.016in) [10].

for design. The calibration to typical allowables yields a D0t = 0.5588mm (0.022in) and a D0c = 0.4572mm (0.018in) which are used for failure load predictions. Finally, correction factors are defined as a function of hole diameter, laminate thickness, and %45 degree fibers. The correction factors modify the characteristic distances to account for varying hole size and fiber percentages. This approach is more physics-based than using a constant, one-size-fits-all bearing allowable because it captures all the variables of the problem such as bearing bypass loads, multi-axial loads, bolt loading direction, layup, bolt diameter, laminate thickness, and wet or elevated temperature material allowables.

2.4 Correction Factors

Fastener dependent factors are used to correct the margins of safety for effects not captured in the FEM and analytical methods. These correction factors used for the CCM fastener analysis are listed in Table 4.

Table 4 - Joint correction factors used for bearing and BJSFM analysis [1]

Fastener Diameter mm (in)	**Eccentricity Factor (Single Shear)**	***Edge Distance Factor (d_e<3D)***	***Hole Diameter Factor****	***Fitting Factor***
9.525 (0.375)	*0.79*	*0.85*	*0.93*	*1.15*
12.7 (0.5)	*0.79*	*0.85*	*0.88*	*1.15*

**Factor used for laminate bearing analysis only*

The load eccentricity factor is applied to both the bearing and BJSFM analysis. This factor is meant to correct for the bending moments present in single shear joints which are not captured in a FEM joining two co-planner meshes. The bolts used throughout the CCM test article are 0.375 inches and 0.5 inches in diameter. For a bearing analysis, assume a constant force over the projected area. In reality, the intensity of bearing force between a fastener and a laminate is not constant, but varies from zero at the edge to a maximum value at the center. For this reason, a hole diameter factor is appropriate for the bearing analysis. The variation of bearing force decreases as the hole diameter decreases, so for smaller fasteners the hole diameter factor has less effect on the allowable bearing stress. A BJSFM analysis determines the strain field around the hole so the use of a hole diameter correction factor is not recommended. The edge distance correction factor is required if the distance from the fastener to a free edge is less than a nominal value (3D). The fitting factor of 1.15 is applied to scale-up the bearing stress in the margin of safety calculation and is typically used for both bearing and BJSFM analysis.

3 Automation Process

3.1 About HyperSizer

HyperSizer software automates the optimization process for stiffened panels, sandwich panels, and open and closed cross-section beams. HyperSizer imports a Finite Element Model and FEA element loads and solves for the resulting ply level stresses and strains, then evaluates the structural integrity using over 100 different failure analyses. The failure analyses include traditional industry methods and modern analytical and computational solutions. Methods development has been on-going since the late 1980's to present.

HyperSizer automates the execution of the BJSFM analysis by passing into the BJSFM code: the laminate definition, all material properties, bearing force, load angle and hole diameter for all fasteners in a global FEM. The BJSFM code computes the laminate stresses in concentric rings around the hole. At the characteristic distance, HyperSizer computes ply-by-ply stresses and strains and calculates the composite strength margin of safety at each angular increment. One of several composite failure criteria is applied to determine the critical margin of safety. The minimum margin of safety is used for laminate sizing optimization.

3.2 Automated FEM Coupling

Unlike metals, composite materials are not ductile and do not yield. As a result, the bearing load distribution in a bolted composite joint is non-uniform. The outer rows of fasteners pick up more bearing force than the inner rows of fasteners, see Figures 11 and 12. The first step in performing a bolted joint analysis is to quantify forces in each fastener. Common practice is to use CBUSH elements to model fasteners in a global finite element model. The CBUSH elements have in-plane stiffness which provides a load path from the metallic fittings to the composite skin. Using this modeling technique, the forces from CBUSH elements are quantified as bearing forces in the laminate.

To automate the load extraction, HyperSizer imports each FEA-computed CBUSH element force for all mechanical and thermal load sets. Several analysis steps are automated with this approach such as the handling of multiple load cases, computing the load angle, and calculating the bypass loads around the fastener. Then the bolted joint analysis is performed on every laminate in the FEM. For a laminate containing multiple CBUSH elements, the bolted joint analysis is performed for each CBUSH element that references the same laminate, see Figure 13. The corresponding minimum margin of safety, effective bearing allowable, and controlling load sets are displayed in the HyperSizer Bolted Joint Analysis form.

The Bolted Joint Analysis form, Figure 14, provides options to select the panel concept, location and size of holes, and joint correction factors. The user also selects the fastener force extraction method, the load to consider as bearing or bypass, and the appropriate lamina failure criteria for BJSFM margin of safety. Immediately following the analysis, the results are displayed in the Bolted Joint Analysis form. The analysis results include: the computed bypass loads, the effective bearing allowable, controlling load set and fastener margins of safety based on the user-defined material properties.

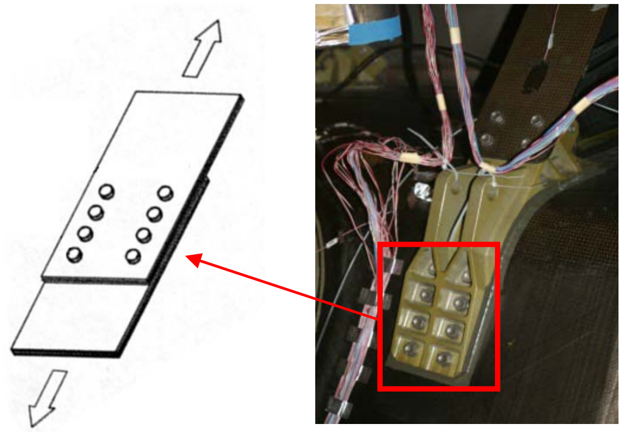

Fig. 11 - Example CCM bolted joint configuration with multiple rows of fasteners.

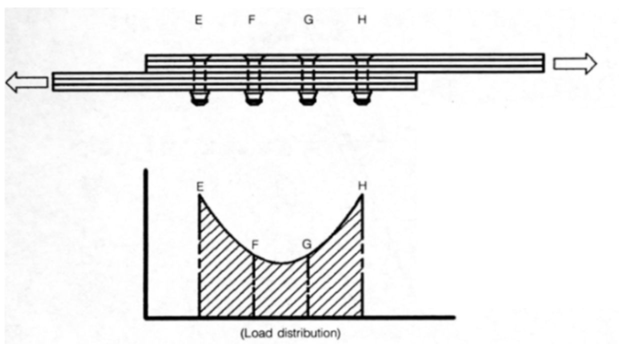

Fig. 12 - A typical non-uniform bearing load distribution for laminates with multiple rows of fasteners[9].

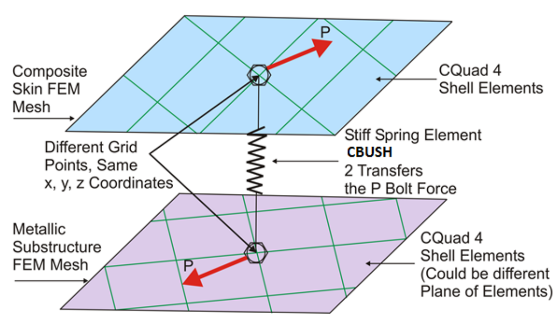

Fig. 13 - A common fastener modeling technique where CBUSH elements connect grid points on co-planer meshes. The CBUSH element has in-plane stiffness which provides a load path from the composite laminate to the metallic fitting.

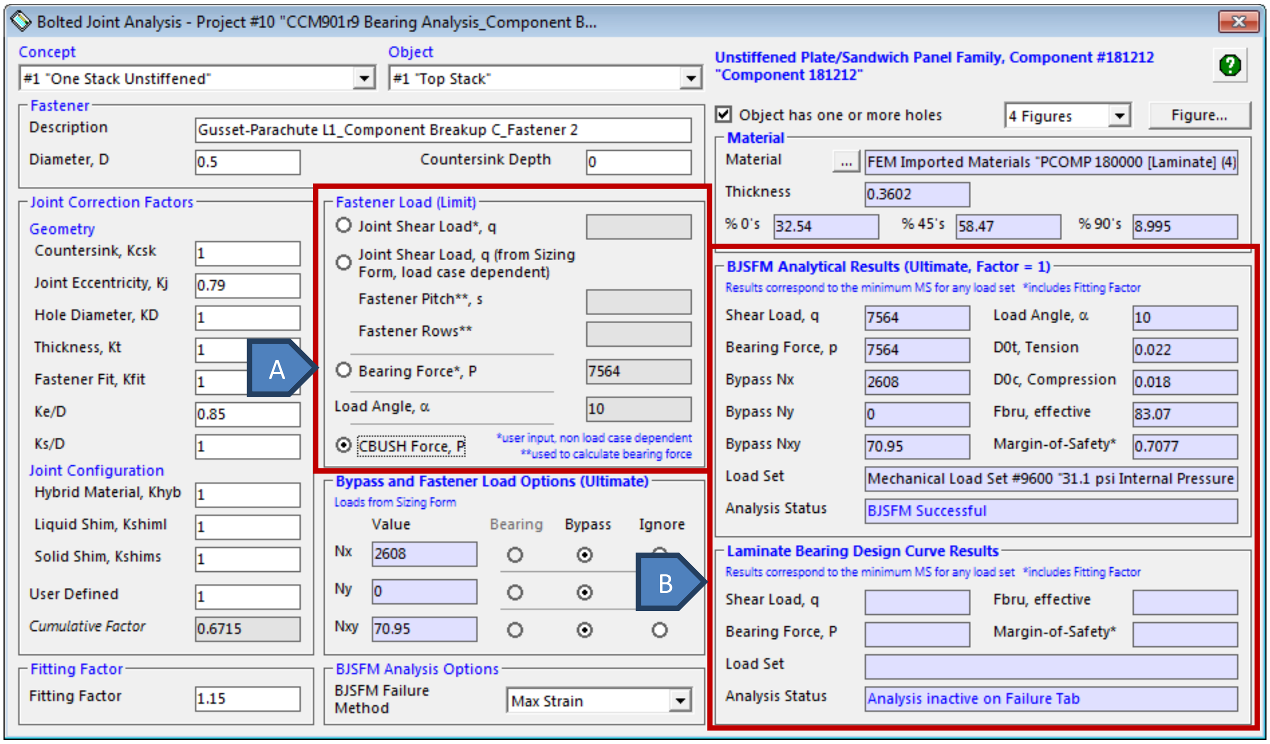

*Fig. 14 - The Bolted Joint Analysis form (*in English units) provides visual inspection of the bearing and BJSFM analysis input and solution data. The input data includes the fastener geometry, bearing load extraction method (A), bypass loads, and material properties. The applied bearing stress is determined from the bearing force, **fbru = P/dt** = [33646 N/(12.7mm*9.15mm) = **290MPa**], [7564lb/(0.5in*0.3602in) = **42ksi**]. The analysis results are displayed in the Bolted Joint Analysis form immediately following the bearing and BJSFM analysis (B). Analysis results include the effective bearing allowable (Fbru), the controlling load sets, and minimum margins of safety.*

3.3 Joint Correction Factors

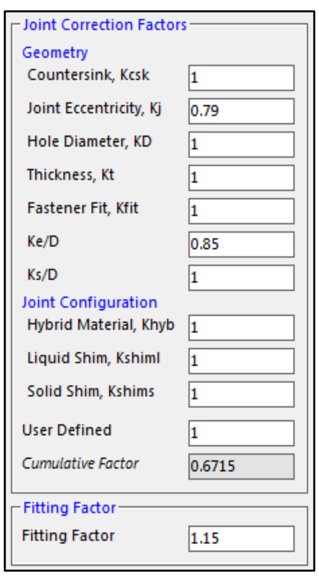

Fig. 15 - User-defined joint correction factors.

The fastener dependent correction factors are used to correct the margins of safety for effects not captured in the FEM and analytical methods. During the bolted joint analysis, the bearing allowable [Fbru] is scaled by the cumulative joint correction factor. Multiple joint correction factors are available for each fastener, see Figure 15. The description of each correction factor is listed in the following section.

The Kcsk correction factor is for fastener head type. Baseline fastener type head is a protruding tension head fastener, Kcsk = 1.0. Since the bolted joint allowables are obtained using a protruding fastener, for countersunk fasteners a typical value, Kcsk < 1.0, is applied to both bearing and BJSFM analysis. The Kj factor corrects for joint eccentricity present in single lap shear joints. Typical single shear factors for solid laminates are 0.7 < Kj < 0.8. For honeycomb structures the fastener is stabilized by the skins and acts as a double shear joint so Kj = 1.0. The hole diameter correction, KD, factor is typically used for a laminate bearing analysis. A constant bearing force is assumed over the projected hole area, however the bearing force between a fastener and a laminate is not constant, but varies from zero at the edge to a maximum value at the center. The thickness correction factor, Kt, is used for a laminate bearing analysis to correct for the laminate thickness. Typically, a Kt < 1.0 is used for thin laminates since thinner laminates have a decreased bearing strength. The Ke/D is the edge distance correction factor.

Common design practice is to use a nominal edge distance (3D) from the fastener hole centerline. Typically, if e/D > 3.0 then Ke/D = 1.0. Ks/D is the fastener spacing correction factor. The nominal distance between fasteners is 4D. If the fastener spacing is less than 4D, a typical fastener spacing correction factor of 0.8-0.9 is applied. Also, if the fastener spacing is much greater than 4D, a fastener spacing correction factor of 0.7-0.8 is required for thin laminates where buckling between fasteners can be a problem. The fitting factor (Kf) is applied directly to margin of safety calculation to account for analysis assumptions and uncertainties (Kf = 1.15). In the margin of safety calculation, the bearing load is scaled down by 1.15.

3.4 Bypass Load Calculation

The bypass loads are computed from the net result of applying bolt force and far field loading. The bypass load for each fastener is determined by a simple force balance, using the bearing force and fastener analysis width (W):

$$Nx_{Bypass} = Nx_{Avg} - \frac{Fx_{Bearing}}{2W} \quad [1]$$

The force balance is expanded to include the load angle and the bypass load in each primary load direction.

$$Nx_{Bypass} = \left(Sign\ Nx_{Avg}\right)\left(\left|\ Nx_{Avg}\right| - \frac{Pcos(\alpha)}{2W_{Yspan}}\right) \quad Ny_{Bypass} = \left(Sign\ Ny_{Avg}\right)\left(\left|\ Ny_{Avg}\right| - \frac{Psin(\alpha)}{2W_{Xspan}}\right) \quad [2,3]$$

Where P= bearing force (lb) and α = load angle.

3.5 Analysis Process

For the CCM bolted joint analysis, the following analysis approach is used to quickly identify the critical fasteners for all test load cases. The FEM shown in the top of Figure 16 defines all composite laminates attached to each fitting as the same property ID (HyperSizer component). This component definition is referred to as Component Definition A. To accurately pair the bypass and bearing loads, the composite around each fastener has to be separated into unique components. However, with over 500 fasteners on the vehicle this would be a very labor-intensive process. During the analysis of Component Definition A, HyperSizer loops through each CBUSH element attached to the composite laminates and identifies critical fittings levels using a simple bearing analysis. The Level 1 Gusset-LIDS, Level 2 Gusset-Parachute and Level 2 Parachute fittings are identified as critical in bearing. For each set of critical fasteners in the upper shell assembly (Gusset-LIDS, Gusset-Parachute, Parachute) the components are redefined so the composite laminates attached to each radial fitting (L1-L6) are represented with a unique component ID.

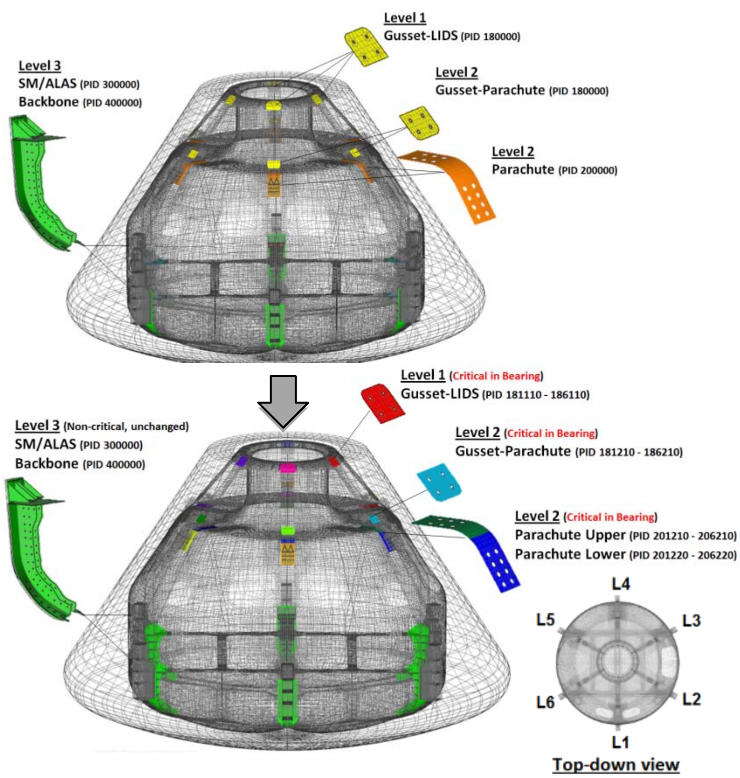

Fig. 16 - (top) Component Definition A, bearing analysis to determine critical fastener levels. (bottom) Component Definition B, bearing analysis on Levels 1 and 2 to determine critical fastener locations (L1 – L6).

This component definition is referred to as Component Definition B. A second bearing analysis is performed on Component Definition B which identifies the L1 Gusset-LIDs and the L4 Main Parachute Fittings to be critical for mechanical load cases 9917 and 9921 respectively.

Since the BJSFM analysis approach is suited for a single fastener, the composite laminates connected to the critical L1 Gusset and L4 Parachute Fittings are separated into unique fastener components, see Figure 17. Each CBUSH element is mapped to a unique property ID, then a BJSFM analysis is performed on each fastener. Using this method, the proper bypass load around the controlling fastener in each bolted joint pattern are quantified. During the analysis, HyperSizer automatically computes the bypass load from the far field loadings and the bearing load extracted from the FEA solution for all test load cases using Equations 2 and 3 on page 10.

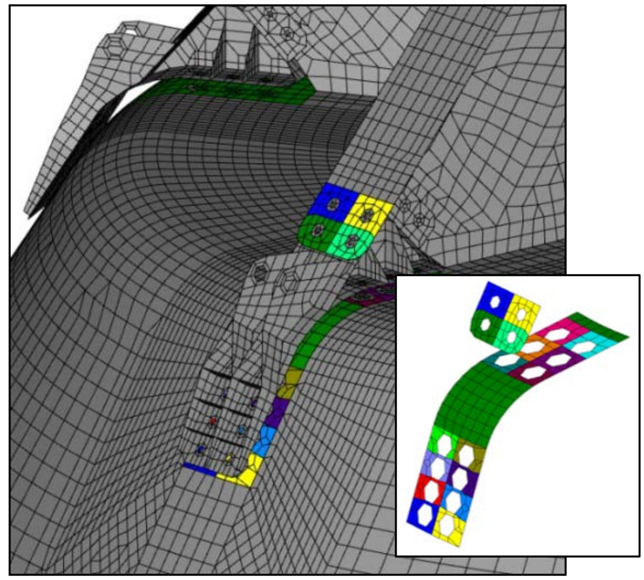

Fig. 17 - Component Definition C, unique PID for each fastener hole in laminate, L4 Main Parachute fitting. BJSFM analysis performed to determine critical fastener locations.

4 Analysis Results

Using the process described in Section 3.5, the margins of safety are quantified for all test conditions. For the test cases with design properties the critical fittings are identified as the L4 Main Parachute Fitting, L1 Gusset-LIDs and L1 Gusset-Parachute Fittings. Select fasteners in the L4 Main Parachute Fitting yield negative margins of safety for load case 9921 which is a concentrated 286 KN (64.4 kip) pull on the L4 Main Parachute Fitting. Fasteners in the L1 Gusset-LIDS and gusset-parachute fittings yield negative margins of safety for load case 9917 which is a concentrated 152 KN (34.2 kip) load on the L1 Fitting.

Since the strain and bearing allowables, used to generate these margins of safety, match damaged design allowables and are not set to match the test environment, negative margins do not necessarily indicate failure during test. The design properties are significantly knocked down due to damage tolerance requirements and since the critical loads determined from these margins are conservative. There was analysis done to match the damage test environment but that analysis was constrained to the prediction of the failure test condition, a pressure condition using hydrostatic pressure.

5 Test Predictions

There are two categories of analysis, test prediction and design. For the test prediction, HyperSizer is used to predict failure of the structure under a set of test conditions. The CCM was tested to destruction on March 2, 2010 with the ultimate pressure load case. Since the maximum internal pressure condition stressed such a large portion of the structure of the CCM, it was the most revealing condition for testing. For safety, a hydrostatic pressure test was performed instead of pneumatic pressure. During the hydrostatic pressure test, the air was allowed to vent as the inverted CCM filled with water. Once full, the vent line was closed off and the water pressure was linearly increased until catastrophic failure occurred. Due to the weight of the water (head) the Hydrostatic Pressure Condition is slightly more critical than the pneumatic pressure condition. All margins presented here correspond to the hydrostatic test condition. All allowables match the damage level or test environment.

5.1 Bearing Analysis Details

For a laminate bearing analysis the critical bearing stress is defined by the “pristine typical” curve in Figure 4. For the 181212 component, a laminate definition of 58% 45 degree fibers yields a bearing stress allowable of 992Mpa (144 ksi). After considering the cumulative correction factor (0.79*0.85*0.88 = 0.59), the effective bearing allowable stress is 585 MPa (85 ksi). The applied bearing stress is calculated using equation 4.

$$fbru = \frac{P}{d*t} = \frac{33.6\,KN}{12.7mm*9.15mm} = 290\ MPa\ (42ksi) \qquad [4]$$

See bearing force in Figure 14. The fitting factor, 1.15 is included in the margin of safety is calculation.

$$MS = \frac{Fbru}{1.15*fbru} - 1 \qquad [5]$$

The $MS_{bearing}$ = 0.76, which is used to predict the internal pressure load which causes failure.

$$Pcr = (MS + 1)*214\ KPa \qquad [6]$$

The predicted bearing failure is at an internal pressure of 377Kpa (55psi).

5.2 BJSFM Analysis Details

For the BJSFM analysis shown in Table 5, the effective bearing stress allowables can be backed out from the computed margin of safety using equation 5. Keep in mind, the HyperSizer margin includes the contribution of the bypass loads. This far field loading causes the hole to elongate, even without bolt bearing. If far field loading is present, it can have a significant impact on reducing the allowable bearing stress. Using equation 6 the BJSFM margin of safety for component 181212 is used to predict the internal pressure load which causes failure.

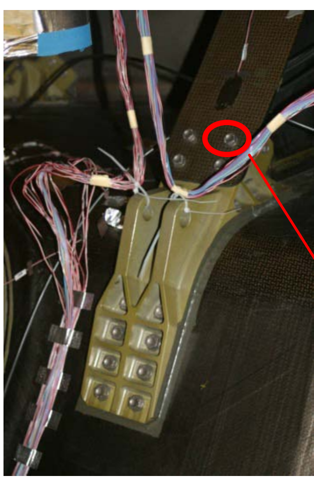

Table 5 - Fastener Failure Predictions for Hydrostatic test, BJSFM margins of safety

Laminate Component ID	Fastener Diameter (mm)	*fbru* Applied Bearing Stress (MPa)	Fbru Effective (MPa)	Margin of Safety	Predicted Failure Pressure (KPa)
181111	9.525	190	812	2.72	795
181112	9.525	200	805	2.50	749
181113	9.525	210	749	2.10	664
181114	9.525	230	749	1.83	606
181115	9.525	180	826	2.99	854
181116	9.525	200	812	2.53	756
181211	12.7	320	637	0.73	370
181212	12.7	290	570	0.71	365
181213	12.7	280	616	0.91	409
181214	12.7	300	651	0.89	404

Note, to get the best correlation to test data the "Mean" or "Typical" open hole allowables are used to calibrate the characteristic distances. The typical properties are identified as the average failure load from a series of identical material tests.

6 Conclusions

For the test cases, using damaged design properties, the critical fittings are identified as the L4 Main Parachute Fitting, L1 Gusset-LIDs, and L1 Gusset-Parachute Fittings. For the hydrostatic test case, with typical properties, the

L1 Main Parachute Fitting is determined to be critical. A bearing analysis predicted failure at an internal pressure of 377 KPa (55 psi) and a more sophisticated BJSFM analysis predicted failure at an internal pressure of 365 KPa (53 psi).

The CCM test article was tested to destruction on March 2, 2010 using a hydrostatic pressure test. The hydrostatic pressure test was terminated at 369 KPa (53.9 psi) after a loud audible noise was heard, followed by a sudden decrease in internal pressure. The identified failure mode was a facesheet delamination failure in the ceiling of the upper pressure shell. The fasteners did not catastrophically fail before the predicted failure load. Due to the variability of lamina test data and the lack of definable bearing failure criterion, predicting fastener failure in a full scale test article is not trivial. To account for the variability in test data, design-to allowables are used for vehicle design.

For vehicle design and analysis HyperSizer significantly reduces the analysis time by providing the ability to analyze a large number of fastener configurations on a global FEM. Without an automated tool such as HyperSizer, fastener analysis studies would take much longer to perform.

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