The HyperSizing Method for Structures

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Abstract

A practical structural optimization system specifically designed for effective engineering solutions is presented. The system, called HyperSizer™ [1], is coupled with finite element analysis (FEA). The system is based primarily on accurate engineering analyses and secondarily on discrete optimization. Its underlying method is a departure from typical finite element design sensitivity and optimization that emphasize numeric optimizers, and model based user defined constraints on strength and stability failure analyses.

HyperSizer's built-in detailed analysis capabilities, and its ease of use makes it suitable as a tool for performing automated structural analyses of any general structure. Indeed, this is the fundamental premise of the HyperSizing method. HyperSizer's ability to predict structural failure will be first presented, and then the benefits of coupling the closed form analytical capabilities with those provided with FEA. The example application is a space launch vehicle, which containing 7 assemblies, 21 optimization groups, and 203 structural components. It demonstrates how an engineer is able to provide 'real-world' expertise in the optimization process by interacting with HyperSizer for *designs on the fly*.

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Introduction

Planes, rockets, automobiles, and ships require FEA to solve their ‘running-loads’, ‘internal loads’, or ‘load-paths.’ In essence, the vehicle FEM is first and foremost used as a 'loads' model for integrating the effects of surface pressure, temperature, and accelerated inertia into element forces and moments. It accomplishes this because the discrete shell elements accurately represent the generalized stiffness of the individual panel and beam structural components of the vehicle design. This forms the **first** premise of the HyperSizing method. That is the loads model does not need to know the actual cross sectional shapes of the panels and beams, nor their composite material layups [1]. The method is robust enough to handle panels and beams with general cross sectional shapes, including those, which are unsymmetric or unbalanced [2].

HyperSizer automates the analysis and optimization of structures by using the FEA computed 'internal' panel and beam forces and moments. These are used to check and avoid the many different types of failures that may occur within a structure [3,4]. The **second** HyperSizing premise is that once the structural component's design-to loads are accurately resolved, potential panel or beam failures can be effectively predicted with explicit, closed form methods. The simplest analogy to this capability is an automated hand stress check performed after the internal FEA loads are computed to determine if they exceed the load carrying capacity of the structural members. These non-FEA based failure analyses, which are quite sophisticated, include material strength, panel biaxial buckling, beam-column buckling, local buckling of flanges and webs, crippling of the cross section, deformation, modal frequency, etc.

A substantial challenge to automating structural analysis and optimization is ‘pulling-loads.’ The problem arises when many finite elements are used to represent a structural component. This is especially true if the panel has varying load from midspan to edge, or from one edge to another edge. Designing to the maximum element load could be far too conservative and result in over-weight. Buckling failure modes are more dependent on integrated type compressive load than an element peak load, which may be located at the panel's corner. A **third** HyperSizing premise is that statistics is the best way to determine the appropriate design-to load.

A **fourth**, and final HyperSizing premise is that optimization of all possible panel and beam design variables of the total structural system is best accomplished with discrete optimization [5]. This is particularly true when there are many in-service loadings subject to many diverse local level design criteria. This approach permutates panel and beam designs based on user-defined upper and lower bounds of each variable. Benefits to this approach as implemented in HyperSizer are that non-numeric optimization variables like material or structural concept can be handled, as well as discrete optimization variables such as number of plies, without the occurrence of local or false optima, and without limitation on problem size. In fact, HyperSizer is able to discretely optimize in a manner that considers material selections and panel or beam concepts in addition cross sectional dimensions, thicknesses, and layups. Using methods to accurately compute margins-of-safety for all potential failures, without depending on the user being able to derive these on his own experience, guarantees structural integrity of the selected optimum design.

The first three of these four premises are discussed briefly below, leaving the bulk of the paper devoted to the aerospace vehicle optimization example.

Generalized stiffness coupling with FEA

HyperSizer is significant due to its generality and ability to be linked accurately with planar finite element analysis (FEA). Non-linear, temperature and load dependent constitutive material data of each composite material's laminate are used to "build-up" the stiffened panel membrane, bending, and membrane-bending coupling stiffness terms and thermal coefficients. These panel data are input into the FEA program to accurately perform analysis with coarse meshed models. The method is robust enough to handle panels with general cross sectional shapes, including those, which are unsymmetric or unbalanced. Traditional methods of formulating equivalent plate panel stiffness and thermal coefficients, though intuitive, are difficult to use for a wide possibility of applications and give incorrect results for thermomechanical internal load distributions [1,2]. A technique of implementing this formulation with a single plane of shell finite elements using MSC/NASTRAN was revealed that provides accurate solutions of entire airframes or engines with coarsely meshed models, Fig. 1. These models produce accurate thermomechanical internal load distributions, Fig. 2 solved with closed form methods.

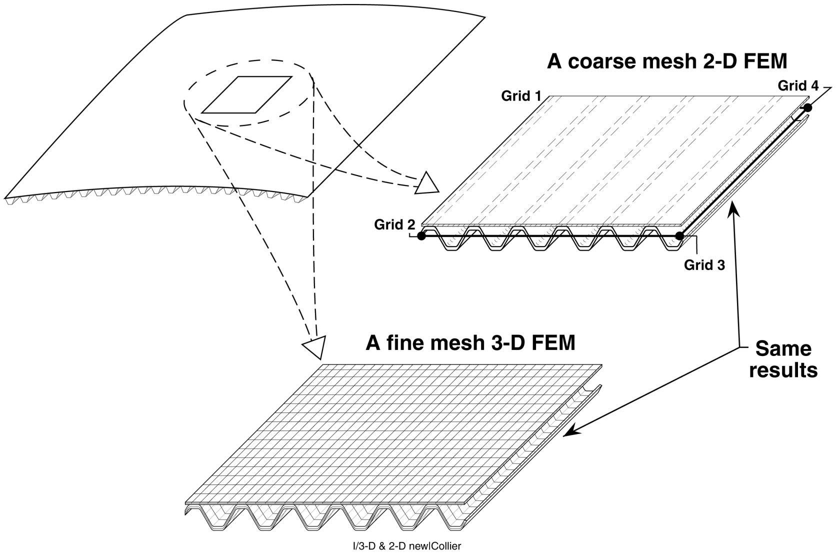


Fig. 1 Genearlized stiffnesses provide accurate FEA.

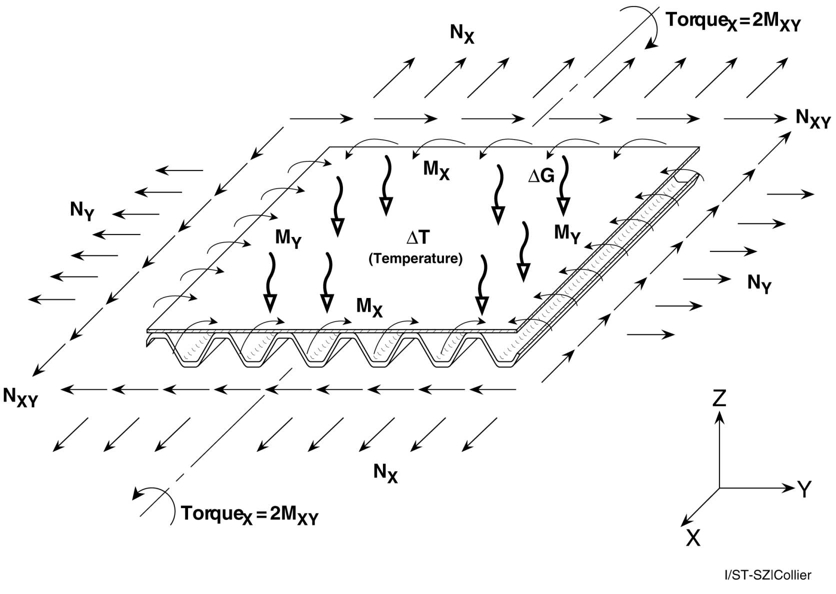


Fig. 2 These FEA produced thermomechanical load combinations can be used accurately by closed form analysis methods.

Closed form, physics based analysis methods

Resulting FEA solved thermomechanical forces and moments can cause many different types of failures to occur within a structure. Some of these failures can be predicted with FEA quite easily, some can be accomplished only with very discrete and finely detailed model meshes (such as local buckling of stiffened panel spans), and then others cannot be effectively accomplished with FEA (such as empirical crippling analyses). In any case, to satisfactorily achieve desired accuracy, many different types of Finite Element Models (FEMs) are usually required in addition to the 'loads model' to predict the multitude of failure possibilities.

Explicit methods can have complete knowledge of detailed design, materials, and design principles including manufacturing constraints, without being hindered by mesh density concerns. HyperSizer's robust automated structural analysis system contains an extensive list of physics based strength, stability, stiffness, and minimum frequency failure analyses as well as provisions to include user defined design criteria such as manufacturing minimum sheet gages and composite material ply layup sequences. By using detailed knowledge of the structure's design, accurate failure analyses can be performed explicitly using the forces and moments from the loads model. In fact, HyperSizer was able to predict the same failure loads, in less than a second each, for the three separate FEMs of Figs 3-5.

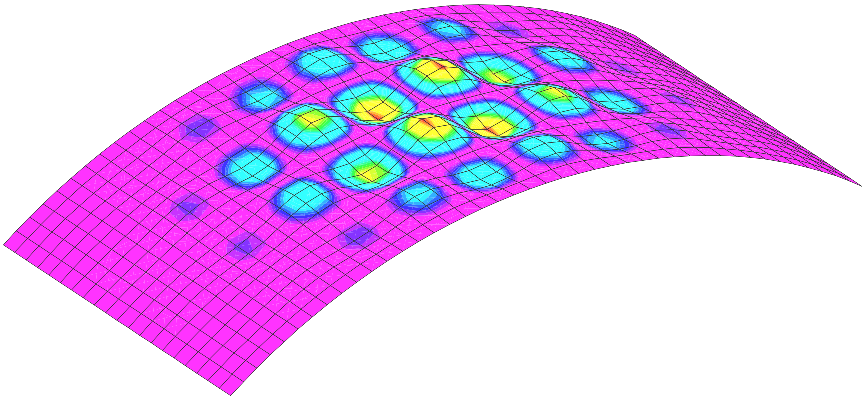


Fig. 3 Biaxial compression buckling of a cylindrical, stiffened fuselage.

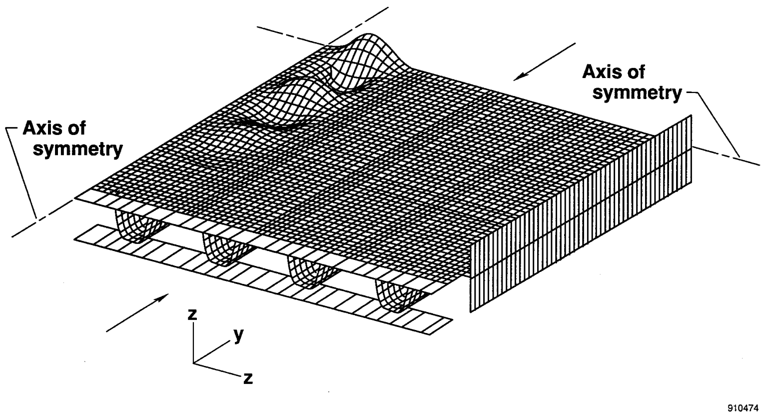


Fig. 4 Local buckling of panel. For benchmark, see page 72 of ref. 4.

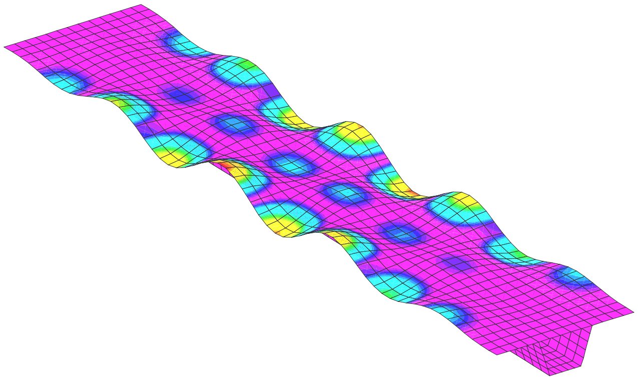


Fig. 5 Local buckling of composite facesheet. See page 153 of reference 3.

FEA computed design-to loads quantified with statistical analyses

Structural analysis is performed using two primary data: applied loadings and allowable loadings. An allowable loading is due to a combination of the material's strength and the nature of the structural design such as panel concept, shape, size, etc. Reliability of a structure is defined as the probability that the allowable load is greater than the required load. Potential failure occurs when the curves overlap in the middle, Fig. 6. The ultimate question being what is the appropriate 'design-to' loading for performing a deterministic structural component analysis.

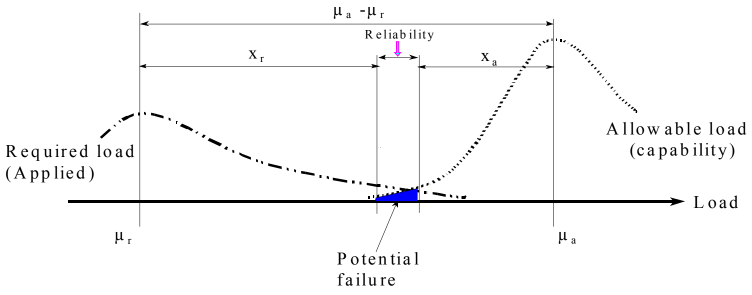


Fig. 6 A statistical approach is used for analyzing potential failure.

The "narrowness" a bell curve distribution is called Kurtosis. A large Kurtosis is desirable because of its narrow width. Unfortunately, as seen in Fig. 6, loadings sometimes have small Kurtosis, i.e. a wider curve causing a larger separation (variance) of the applied loading. The problem is one of determining acceptable levels of load or risk, which is particularly relevant to structural optimization.

$$\text{“Design-to” loading} = \mu + K\sigma$$

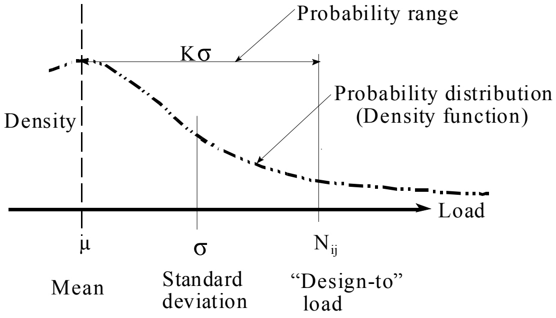


Fig. 7 The HyperSizer user can select the K standard deviation factor for determining the “Design-To” applied loading for strength analysis.

Structural analyses are typically performed using a component’s peak loading without much concern given to the actual load distribution. For components with uniform loadings, i.e. narrowly varying load distributions/large Kurtosis, this approach is sufficient. However for components with widely varying load distributions, i.e. higher loading gradients, this approach becomes overly conservative. The statistical approach of HyperSizer treats the individual force components (N_x, N_y, N_{xy}, M_x, M_y, M_{xy}, Q_x, Q_y,) of each element of a structural component, in essence, as if they were a frequency distribution, or a probability histogram. In this way, the *K factor* (referred to as K sigma, such as 3σ) identified in Fig. 7 is now used to achieve the desired *confidence limit* of the component’s area which is experiencing a level of load. As a result, for a one-sided distribution, a K factor equal to 1, 2, or 3 indicates 84.13, 97.72, and 99.86 % of the component’s area.

Optimizing the total structural vehicle

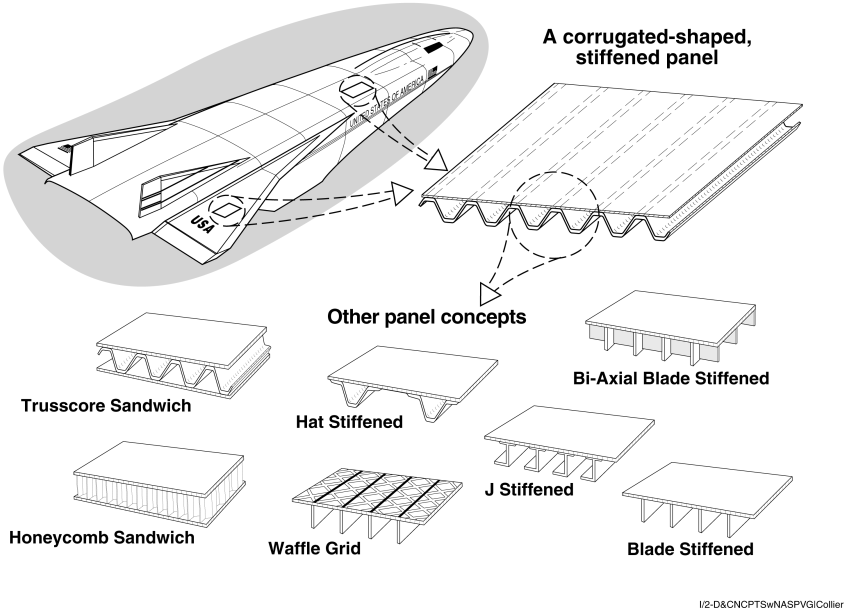


Fig. 8 Discrete optimization permits the optimum selection of panel concept for all surface areas.

The ability to optimize a total structural system with all design variables is fundamental with HyperSizer, Figs 8 and 9. Since finite element sensitivity analysis and numerical optimizers are not used in this approach, there is no exponential relationship between run time and model size/number of design variables. In fact, the only model size limitation is based on practical limits of the linear static solver and pre/post processors. Run times are quick and do not have local minimum solutions that possibly occur with numerical optimization. Fast response is important for the user to be able to keep focus. Immediate feedback on optimization selections, given automatically, helps the user to interact with the solution process and to be able to stay on track with his design thoughts.

An advantage of using explicit solutions is that analyses are accomplished rapidly and can consider the multitude of failure modes and loadcases. HyperSizer's purpose is to include all possible failure modes in the assessment of a possible design. The objective is that the user should be able to depend on the software for capturing all physics based structural integrity checks. As an example taken from reference 6, page 20, in the process of a optimizing a beam, the HyperSizer user need not provide a constraint on the maximum allowable beam height to width ratio because in addition to simple bending stress criteria, HyperSizer would also investigate twisting, lateral-torsional buckling etc.

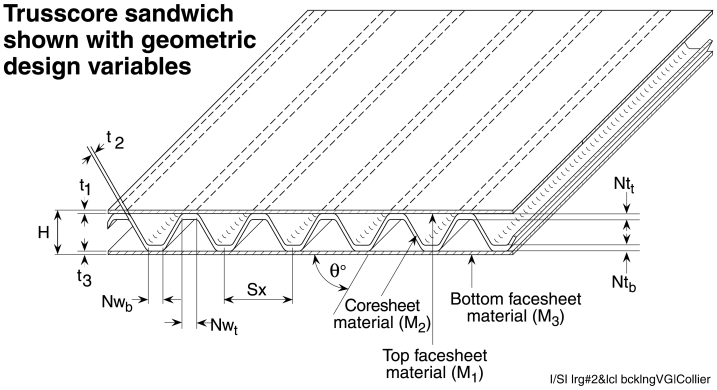
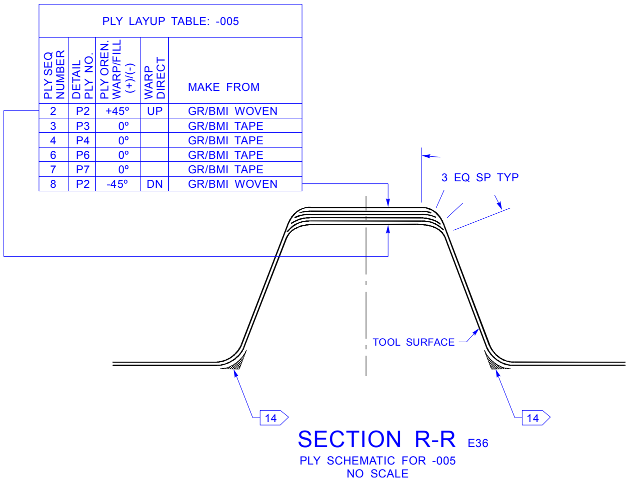


Fig. 9 All aspects of the structural design are optimized

- Panel and beam concepts
- Material selections
- Cross sectional dimensions, thicknesses and layups
- Layups are even customizable to include odd angles and ply dropoffs using an integrated composite layup builder



PLY LAYUP TABLE: -005

PLY SEQ NUMBER	DETAIL PLY NO.	PLY OREN. WARP/FILL (+)/(-)	WARP DIRECT	MAKE FROM
2	P2	+45°	UP	GR/BMI WOVEN
3	P3	0°		GR/BMI TAPE
4	P4	0°		GR/BMI TAPE
6	P6	0°		GR/BMI TAPE
7	P7	0°		GR/BMI TAPE
8	P2	-45°	DN	GR/BMI WOVEN

Optimization input data is easy to select. Optimization bounds can be assigned to different vehicle locations quickly, referred to as *groups*. Optimization solutions are determined for components, which are a subset of groups. *Components* are defined during the process of constructing the FEM and usually represent the smallest piece of manufacturable structure. That is structure fabricated with all of the same design dimensions such as stiffener spacing, panel height, web thickness, facesheet thickness, layups, etc. Visual interpretation is provided automatically for the current panel concept, component, and group.

About the Model

The model represents a NASA designed two-stage-to-orbit aerospace plane requiring accurate analysis capabilities to account for a complex thermomechanical environment. The integrated airframe/engine design contains a large volume of pressurized cryogenic fuel. Internal bulkheads serve as shape control members to maintain the vehicle's shape. The aeroshell is designed to be graphite/epoxy, hat-shaped stiffened panels.

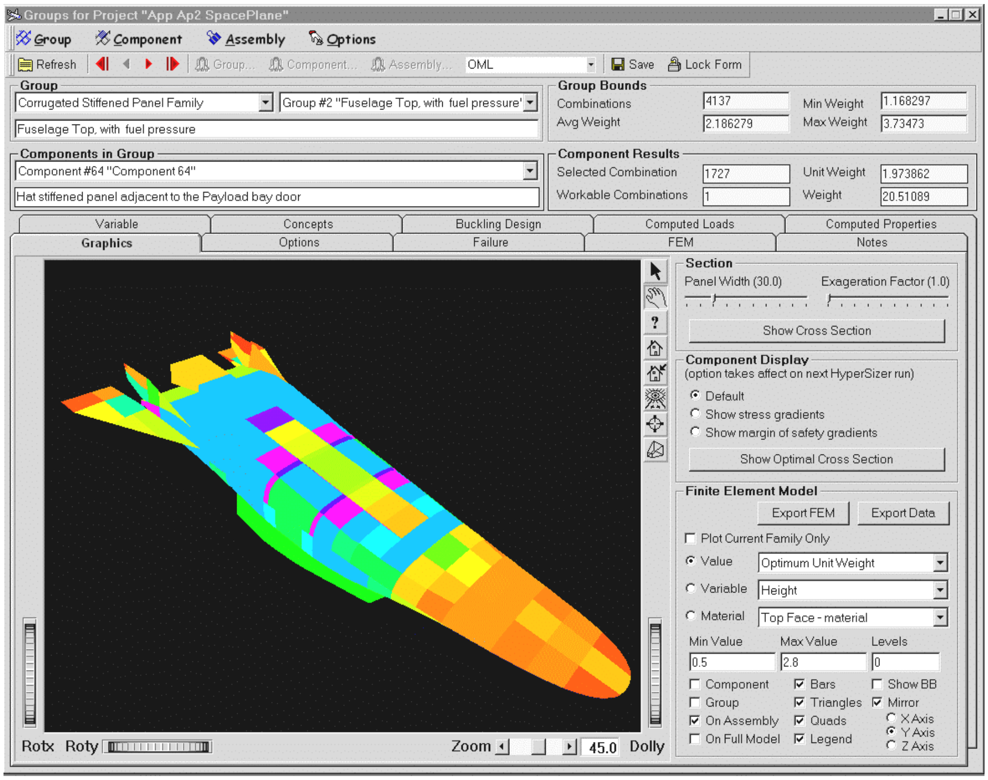
Though HyperSizer can analyze and optimize FEMs as large as one million DOFs, the choice was made to build a relatively small model of approximately 30,000 degree of freedoms (DOF) for the aerospace vehicle. This allows us to take advantage of HyperSizer's unique panel and beam stiffness formulations that achieve accuracy with coarsely meshed MSC/NASTRAN FEMs.

Interaction between the engineer and the software is key to HyperSizer's design process

Engineers learn within seconds the strengths and weaknesses of their structural designs from the software's interactive reporting of margins-of-safety. Interactive 3-D graphics provide visual inspection of the structural component layout, assemblies, and drawn to scale optimum panel and beam cross sections. See Fig. 10. These features are used on the aerospace plane to quickly interpret and understand design flaws. Critical design issues were identified and resolved early in the design process, allowing ample time to perform many design trade studies. This quick and highly interactive process makes the task of saving weight easy and fun.

Conclusion

The commercially available HyperSizer™ detailed analysis and sizing optimization program, which is integrated with FEA, is described using an aerospace example. The example model is a reusable launch vehicle referred to as an aerospace plane. It contains 7 assemblies, 21 optimization groups, and 203 structural components. FEA is used for predicting internal loads. The entire plane is optimized for minimum weight with both composite and metallic materials. Structural integrity is ensured because of over 100 different failure analyses considered by HyperSizer that included strength, buckling, crippling, deformation, and frequency. Run times on a Pentium workstation ranged from two to ten minutes for the entire vehicle.



Groups for Project "App Ap2 SpacePlane"

OML

Group

Corrugated Stiffened Panel Family

Group #2 "Fuselage Top, with fuel pressure"

Fuselage Top, with fuel pressure

Group Bounds

Combinations	4137	Min Weight	1.168297
Avg Weight	2.186279	Max Weight	3.73473

Components in Group

Component #64 "Component 64"

Hat stiffened panel adjacent to the Payload bay door

Component Results

Selected Combination	1727	Unit Weight	1.973862
Workable Combinations	1	Weight	20.51089

Section

Panel Width (30.0)

Exageration Factor (1.0)

Component Display

(option takes affect on next HyperSizer run)

● Default

○ Show stress gradients

○ Show margin of safety gradients

Finite Element Model

☐ Plot Current Family Only

● Value: Optimum Unit Weight

○ Variable: Height

○ Material: Top Face - material

Min Value	Max Value	Levels
0.5	2.8	0

☐ Component ☑ Bars ☐ Show BB

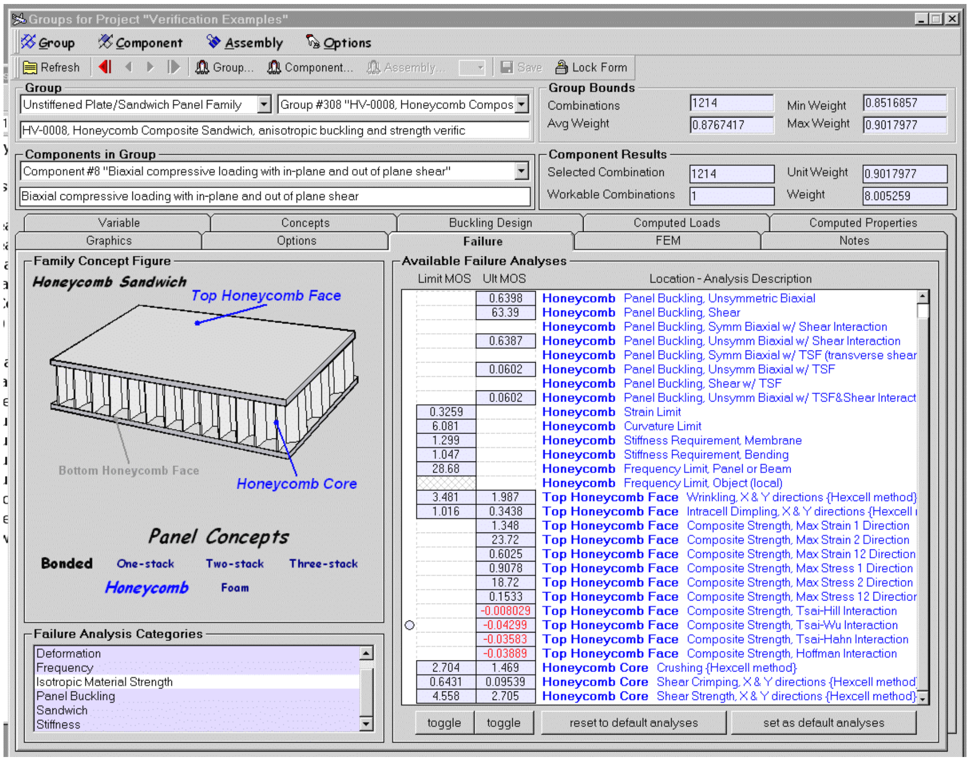
☐ Group ☑ Triangles ☑ Mirror

☑ On Assembly ☑ Quads ○ X Axis ● Y Axis

☐ On Full Model ☑ Legend ○ Z Axis

45.0

Fig. 10 Interactive display tools illustrate the computed optimum panel unit weights margins-of-safety on the assembly called 'OML'.



Groups for Project "Verification Examples"

Group

Unstiffened Plate/Sandwich Panel Family

Group #308 "HV-0008, Honeycomb Compos

HV-0008, Honeycomb Composite Sandwich, anisotropic buckling and strength verific

Group Bounds

Combinations	1214	Min Weight	0.8516857
Avg Weight	0.8767417	Max Weight	0.9017977

Components in Group

Component #8 "Biaxial compressive loading with in-plane and out of plane shear"

Biaxial compressive loading with in-plane and out of plane shear

Component Results

Selected Combination	1214	Unit Weight	0.9017977
Workable Combinations	1	Weight	8.005259

Family Concept Figure

Available Failure Analyses

Limit MOS	Ult MOS	Location - Analysis Description	
	0.6398	**Honeycomb**	Panel Buckling, Unsymmetric Biaxial
	63.39	**Honeycomb**	Panel Buckling, Shear
		Honeycomb	Panel Buckling, Symm Biaxial w/ Shear Interaction
	0.6387	**Honeycomb**	Panel Buckling, Unsymm Biaxial w/ Shear Interaction
		Honeycomb	Panel Buckling, Symm Biaxial w/ TSF (transverse shear
	0.0602	**Honeycomb**	Panel Buckling, Unsymm Biaxial w/ TSF
		Honeycomb	Panel Buckling, Shear w/ TSF
	0.0602	**Honeycomb**	Panel Buckling, Unsymm Biaxial w/ TSF&Shear Interact
0.3259		**Honeycomb**	Strain Limit
6.081		**Honeycomb**	Curvature Limit
1.299		**Honeycomb**	Stiffness Requirement, Membrane
1.047		**Honeycomb**	Stiffness Requirement, Bending
28.68		**Honeycomb**	Frequency Limit, Panel or Beam
▨		**Honeycomb**	Frequency Limit, Object (local)
3.481	1.987	**Top Honeycomb Face**	Wrinkling, X & Y directions {Hexcell method}
1.016	0.3438	**Top Honeycomb Face**	Intracell Dimpling, X & Y directions {Hexcell
	1.348	**Top Honeycomb Face**	Composite Strength, Max Strain 1 Direction
	23.72	**Top Honeycomb Face**	Composite Strength, Max Strain 2 Direction
	0.6025	**Top Honeycomb Face**	Composite Strength, Max Strain 12 Direction
	0.9078	**Top Honeycomb Face**	Composite Strength, Max Stress 1 Direction
	18.72	**Top Honeycomb Face**	Composite Strength, Max Stress 2 Direction
	0.1533	**Top Honeycomb Face**	Composite Strength, Max Stress 12 Directior
	-0.008029	**Top Honeycomb Face**	Composite Strength, Tsai-Hill Interaction
	-0.04299	**Top Honeycomb Face**	Composite Strength, Tsai-Wu Interaction
	-0.03583	**Top Honeycomb Face**	Composite Strength, Tsai-Hahn Interaction
	-0.03889	**Top Honeycomb Face**	Composite Strength, Hoffman Interaction
2.704	1.469	**Honeycomb Core**	Crushing {Hexcell method}
0.6431	0.09539	**Honeycomb Core**	Shear Crimping, X & Y directions {Hexcell method}
4.558	2.705	**Honeycomb Core**	Shear Strength, X & Y directions {Hexcell method}

Failure Analysis Categories

- Deformation
- Frequency
- Isotropic Material Strength
- Panel Buckling
- Sandwich
- Stiffness

The graphical display of analysis and design results is shown to provide the engineer with a powerful insight into the structural problem, and in so doing, allows 'real-world' expertise in the optimization process. The analytical methods and general approach of this integrated tool apply to FEA users in other industries.

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