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DESIGN OF NEW PARAMETERS FOR EVALUATION OF LOAD CAPACITY OF SEMI-SHELL STRUCTURES

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Abstract: *This paper presents the design and research of new specific parameters for faster determination of the load capacity of metal thin-walled semi-shell structures. The graphic visualization and evaluation of the avalanche propagation start is an additional method of load capacity determination based on results of analytical methods. New parameters were tested on evaluation of typical fuselage and stabilizer sections of a small transport aircraft in CS-23 regulation category.*

Keywords: Load capacity, Semi-shell, Stress analysis, Failure, Fuselage.

1. Introduction

Typical aircraft thin-walled metal structures are stiffened semi-shells, which are widely employed in aeronautical industry. These characteristic structures are composed of number of longitudinal stringers stiffening the outer thin shell skin. The example of semi-shell fuselage structure is presented in Fig. 1. A critical stage of the structural integrity is the global load capacity. After this stage the structure is not more able to support the outer load and the total collapse of structure will occur. Determination of the global load capacity is a complex analysis where particular element failures are investigated according to the detailed stress analysis. The critical point of the evaluation is the decision, when the limiting stage is reached and which element failure will start the avalanche propagation of following failures. Standard geometric parameters are utilized in graphic evaluation of changes in structural integrity per load increment. This article describes the design of new specific parameters for more efficient and faster determination of the structural load capacity.

The comprehensive reviews on stability failures of loaded shells in aerospace structures are presented in Niu (1999) and Kollár et al. (1984). This topic was extended in the interesting paper Hoff (1967) and Horák et al. (2016). Analytical solutions of skin buckling and effects of stringer torsional and warping failures and the verification by finite element methods are presented in Soares et al. (2013). The paper by Symonov et al. (2013) contributed with a comparison of utilized analytical gradually increased load method with nonlinear FEM approach of stiffened fuselage structure.

2. Methods

The stress analysis in selected sections of the structural part and the determination of skin and stringer failures was done using the Gradually increased load method GILM. This analytical method is based on the procedure described in Píštěk et al. (1987). Input allowable element stresses were derived separately according to Niu (1999). The applied load is gradually increased in each step and the following weakest structural element and its properties are investigated. This order of the development of element failures represents the history of load and changes of structural rigidity. The global load capacity of the structural section can be evaluated according to these results. The determination of the load capacity of semi-shell structure with significant elements is simple. The failure of significant structural element can be the stability damage of lower compressed flange or the rupture of upper tensioned flange of spars. The critical failure which starts the avalanche propagation of following failures and causes the total collapse is very difficult to derive for the semi-shell structure without significant elements. Typical example is fuselage structure, which is stiffened with longitudinal stringers with similar shape and cross-sectional area.

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History of failures of structural elements obtained from analytical method can be ordered in table. The percentage of load of the particular element failure as well as its geometrical properties and remaining element stress are presented in Tab. 1. It is difficult to determine critical failure of total collapse or start of avalanche failures only from numbers in the table. The buckling failure of the first stringer S52 can be conservatively assumed as the critical failure. Experimental tests proved that the semi-shell stiffened structure can be still sufficiently rigid to support the load after few stringer failures. Therefore the graphic evaluation was employed as the post-processing visualization of analytical method.

Tab. 1: Order of particular failures and element properties in results of load capacity analysis.

Order of failure	**Load coefficient [-]**	**Percentage of load [%]**	**Name of element**	**Element area Ai [mm^2]**	**Second mom. Jzi [mm^4]**	**Element stress [MPa]**
1	0.241	24.1	**P24-27**	105.7	95846620	-7.4
2	0.242	24.2	**P27-30**	138.4	117679387	-7.4
3	0.390	39.0	**P30-33**	121.2	83021059	-21.0
4	0.502	50.2	**P49-52**	206.5	30858354	-13.5
…						
20	1.595	159.5	**P66-68**	69.4	39485107	-20.4
21	1.726	172.6	**S52**	48.6	26138856	-68.5
22	1.763	176.3	**S49**	48.6	3109175	-68.5
…						
28	2.036	203.6	**S55**	56.9	27671443	-86.3

The simulation of particular drop of certain parameter per load increment due to damage is presented in Fig. 1. The order of failures, location on load axis and change of characteristics on vertical axis was determined from analytical gradually increased load method. The level 100 % at the load axis represents ultimate level of applied outer load. The unit formulation, where the drop of parameter is related to the initial sectional characteristic, is utilized in graphic evaluation. The start of avalanche propagation of failures can be determined as the failure, which causes the drop of parameter under the level 50 % or 35 % of initial characteristics. Total initial characteristics are marked with the index 0. The gentle slope of drops of characteristics in Fig. 1 is caused by visualization of standard geometrical parameters.

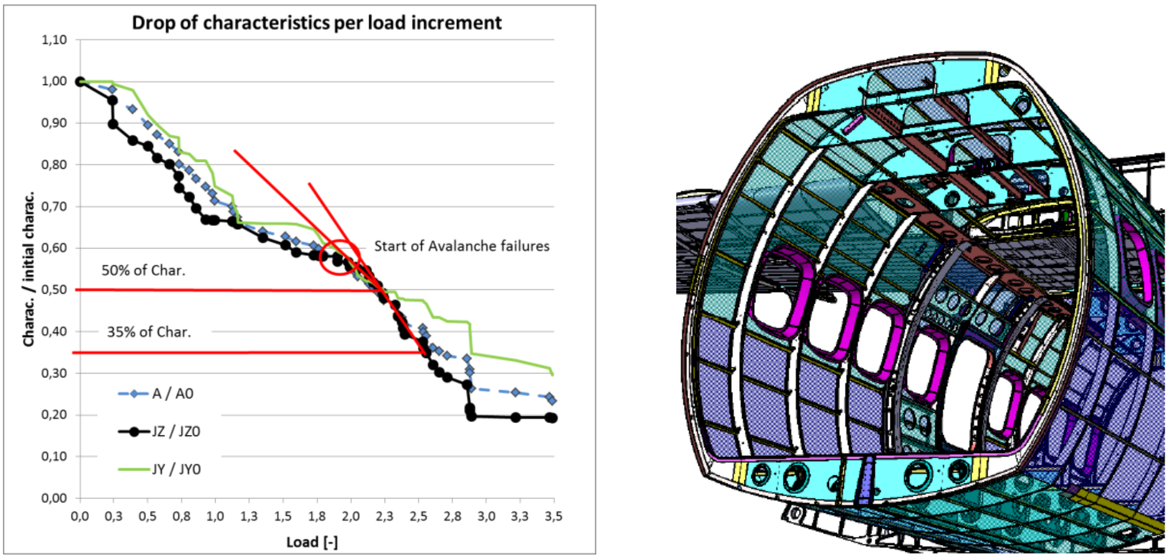

Fig. 1: Drop of geometric characteristics per load increment and typical fuselage structure.

3. Standard parameters

The typical skin and stringer elements were selected for further evaluation from Tab. 1. The shell skin region P49-52 has a large cross-sectional area due to distance between stringers S49 and S52. Element properties are presented in Fig. 2. Also the skin location on outer circumference creates significant second moment of area Jz along the z axis. The longitudinal stringer segments S52 and S49 have identical cross-sectional area, but the increased distance of S52 from z axis results in higher second moment of area Jz than stringer S49. These standard geometric parameters can be used in evaluation of global load capacity but it is not complete information about importance and utilization without element stress.

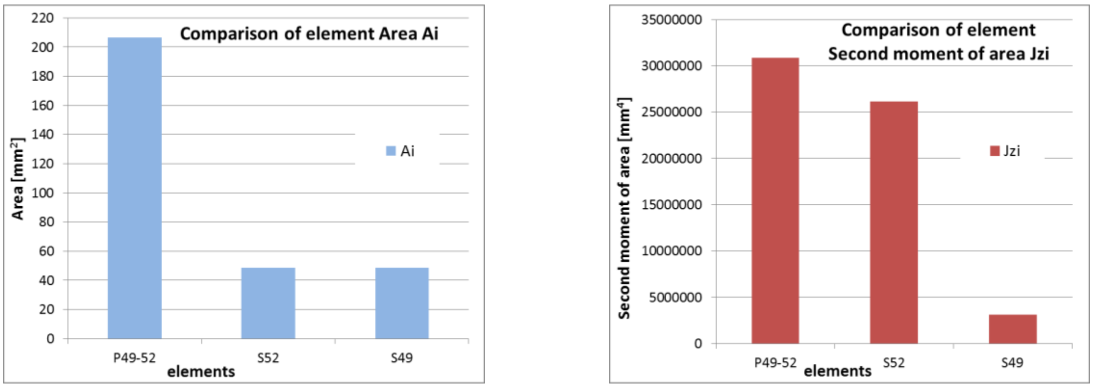

Fig. 2: Comparison of standard parameters of selected elements.

4. Design of new parameters

Although the skin segment P49-52 has the highest area A and second moment of area Jz in comparison with stringers the induced critical stress in this skin element is minor. Therefore this skin region is not utilized as significantly as stringer segments. Stringer segments with minor area are more utilized in structural rigidity due to significant critical stresses. They are subjected to carry higher stresses and support the structure in higher levels of applied load, when skin regions are deformed and buckled. Standard geometric parameters are not able to provide sufficient information about importance and utilization of each element. Therefore additional parameters were designed. The combination of cross-sectional element area and conjugated element stress is represented by Sigma·A parameter. Following combinations of second moment of area and allowable stress of single element created Sigma·Jz and Sigma·Jy parameters. A comparison of element Sigma·Jz parameter is in Fig. 3, where stringer segment S52 demonstrates major effect in the structural integrity in bending along z axis. The failure of this S52 segment will cause the major drop of rigidity per load increment.

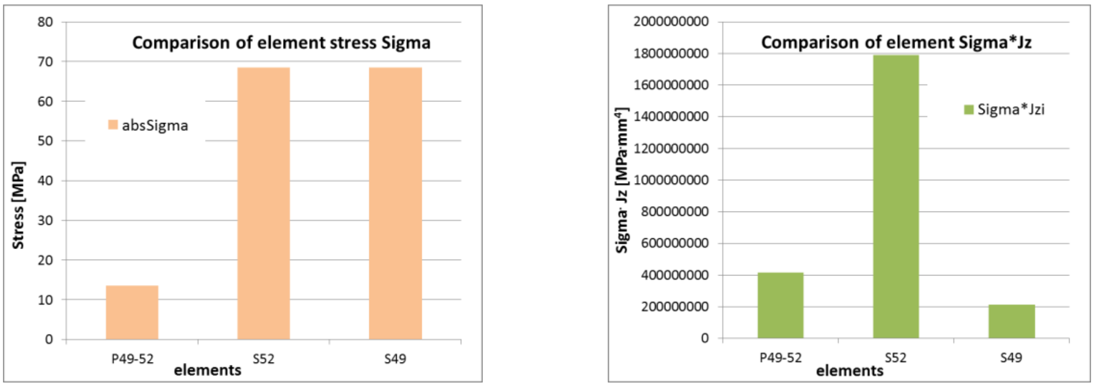

Fig. 3: Comparison of additional parameters of selected elements.

5. Evaluation of results

Suitability and importance of new parameters in graphic evaluation of load capacity is validated in this chapter. Typical fuselage and stabilizer sections of small transport aircraft in CS-23 regulation category were tested as appropriate representatives of metal thin-walled semi-shell structures. The particular drops of Sigma·A, Sigma·Jz and Sigma·Jy parameters per load increment were simulated for a typical semi-shell fuselage section without cut-outs. It is beneficial that graphic visualizations are more sensitive to significant stringer failures than to minor skin failures. The comparison of effects of standard and new parameters for identical load case is presented in Fig. 4. Stability damages of skin regions in initial increments of the load and following compression failures are characteristic also in behavior observed from experimental tests. The stability failure of the first stringer segment S52 was determined by analytical method at the level 172.6 % of the ultimate load. A steep slope of drops of characteristics facilitates to determine the significant element which starts the avalanche propagation of following failures and causes the total collapse of the structure. A detailed investigation with new parameters determined critical failure of stringer S43 at the level 190.2 % of the ultimate load. This superior predicting method increased the global load capacity of about 17.6 %.

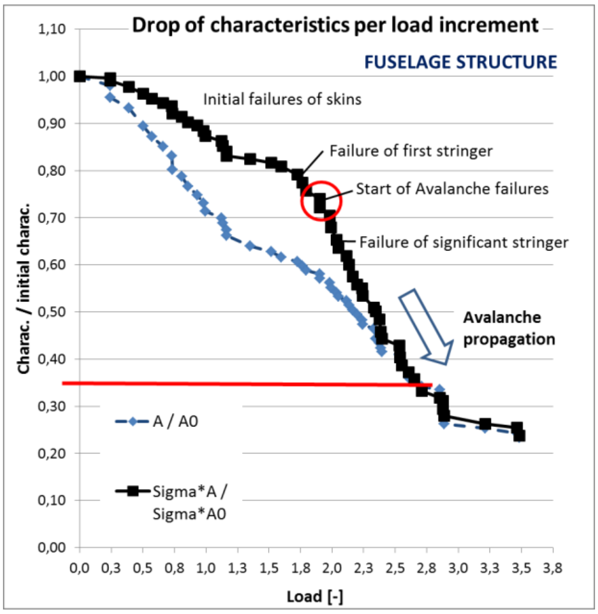

Fig. 4: Drop of parameters per load increment in fuselage section.

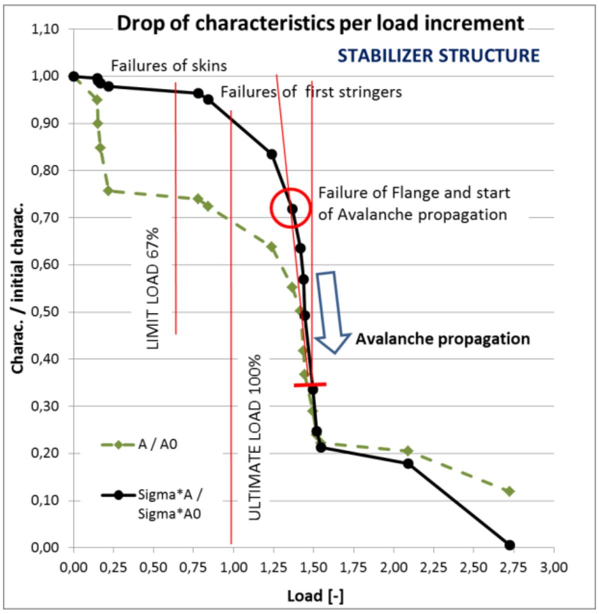

Fig. 5: Drop in stabilizer section.

Benefits of graphic evaluations with new parameters were confirmed also for stabilizer section in Fig. 5. The critical failure of flange was evaluated at the level 137 % of ultimate load.

6. Conclusions

The detailed research of new specific parameters confirmed more effective evaluation of the start of avalanche propagation of element failures. This additional method of determination of the critical element failure can improve the evaluation of the global load capacity for thin-walled metal semi-shell structures.

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