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The Effect of Imperfections on the Prediction of the Stability Loss of Composite Shear Panels

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Abstract. The aim of this work was to gain a general overview of the behaviour of composite materials when their stability is lost. For this purpose, one monolithic laminate and one sandwich plate specimens were chosen that were both loaded with a diagonal force. The models of these tasks were created in FEM software. The problem could not be solved by standard linear buckling analysis tools as they are unable to model deformation shapes after loss of stability. The load bearing capacity could thus be investigated only until the critical force of the loss of stability. However, in some cases, it can be assumed that the loss of stability could be very close to the real bearing capacity of the panel, therefore the task was modelled by both linear buckling and nonlinear buckling (with application of imperfections). After the FE analysis an experimental measurement was performed in order to show the precision of simulation and the quality of model. The results of the FE analysis were compared with experimental results.

Introduction

Composite materials have been used in various areas of industry for a long time. Their field of application is still growing and new materials with more beneficial properties are still being developed. However, unlike metals and other materials, composite materials do not tend to create permanent strain before failure, therefore careful consideration should be given to their design and to experimental verification of their properties. Composite structures can be stressed by all kinds of loads such as tension, compression, torsion, bending etc. The limit state of a composite structure loaded in compression can occur when the compressive strength is exceeded or the stability of the structure is lost (buckling). Therefore, it is necessary to understand this phenomenon that occurs when the limit values are reached [1].

The concept of buckling is closely related to the concept of equilibrium. The graph in Fig. 1 shows the so-called equilibrium paths. As the load increases, the loaded structure initially follows its primary equilibrium path, also called the pre-buckling path. In linear buckling, the pre-buckling path ends at the bifurcation point. This point represents the critical load value, also known as the buckling load, at which a sudden change in deformations occurs. Large deformations can result in the immediate failure of the loaded structure. The value of the point is predicted by eigenvalue analysis. From the bifurcation point, the equilibrium path continues along the secondary equilibrium path, also called the post-buckling path. The increasing slope of the post-buckling path indicates that the structure has a load carrying capacity to resist the load after buckling. This equilibrium path is called stable. The decreasing slope of the post-buckling path indicates that the structure is not able to resist the load after buckling. The buckling load in this case is the maximum load of the structure. This equilibrium path is called unstable. In a nonlinear buckling, where structure imperfections are considered, the equilibrium path has a significantly smoother course. The primary equilibrium path ends here at the failure point, which represents the load at which the structure collapses. The value of the failure point can be predicted by nonlinear analysis [2].

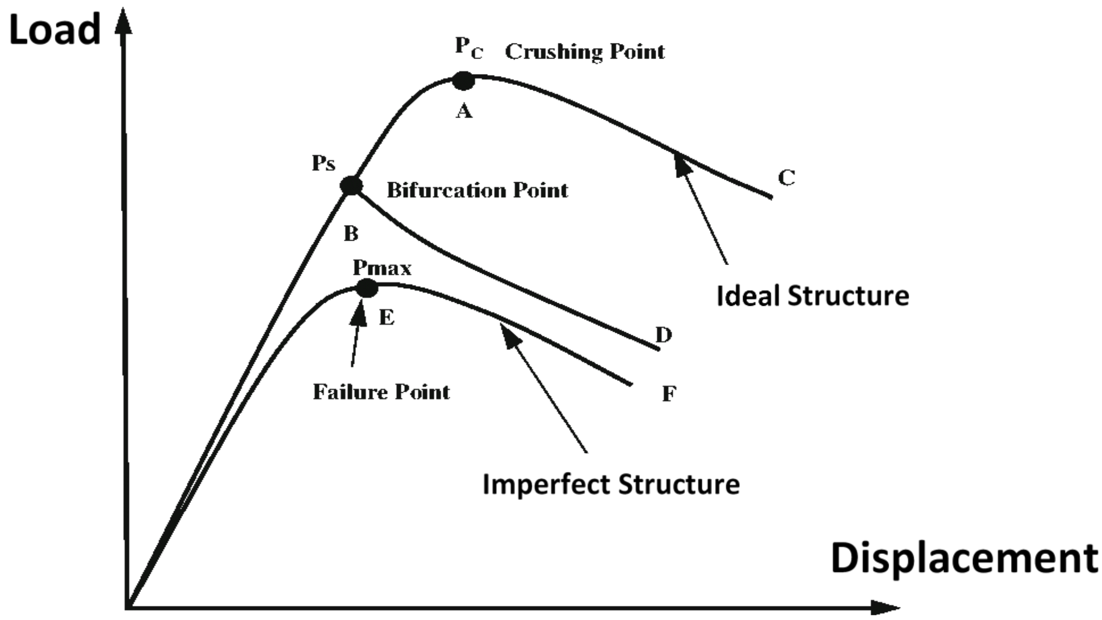

Fig. 1: Equilibrium paths for linear and nonlinear buckling [3]

The loss of stability of the composite panels results in a two-dimensional sine deformation out-of-plane of the panel. As the load increases, the panel shortens in the load direction until stability is lost. After loss of stability, the panel is able to carry the load further, anyway only with reduced stiffness. It is the difference from the loss of stability of the rod, where the load at the loss of stability is the ultimate load.

Special attention should be paid to the loss of stability of sandwich panels. A sandwich panel is made of two thin skins bonded to a core of a lightweight material of greater thickness. The skins transfer load (tension/compression, shear and bending) in-plane of sandwich panel while the core transfers load in out-of-plane direction (shear). Failures of sandwich panels can be divided into three basic categories: insufficient strength, loss of local stability and loss of overall stability. The insufficient strength is caused by exceeding the skin, the core or the interface strength limit. The loss of local stability is caused by too low skins thickness, however too large honeycomb cells size must be also considered. A typical mode of the loss of local stability is wrinkling. The loss of overall stability does not result in skins or core failure, which occurs only under continuing loading. A typical mode of the loss of overall stability is crimping. It usually appears suddenly and it seems as the loss of local stability, but in fact it is sort of the loss of overall stability [1, 4].

The stability of sandwich materials is influenced by a wide range of parameters. The most important ones include boundary conditions and imperfections. Imperfections can be caused by damages and inaccuracies that are formed both in the manufacturing process and in the service. They may occur in form of cavities, delaminations, debondings, cracks in matrix, fractures of fibres etc. These damages are often not visible and easy detectable, but they can cause considerable stiffness degradation and affect strength and stability of a structure. Theoretical predictions and models always require a comprehensive knowledge of geometric and material characteristics, boundary conditions and considerable amount of other influences that are not easy to determine. Including imperfections, the models become much more complicated to solve [1].

The paper tries to quantify the influence of shape imperfections of typical composite structures on the loss of its stability. For this purpose, monolithic laminate and sandwich panels loaded by in-plane shear were chosen.

Description of test specimens

Two composite panels were tested. The first one was a sandwich panel. The sandwich panel consisted of Nomex honeycomb core (cell size 3.2 mm, density 29 kg/m^3) at thickness 5 mm and 2 composite skins. The skins were made of one ply of EP121-C20-45 prepreg with carbon fabric reinforcement (Twill 2/2, 204 g/m^2) and epoxy resin oriented at 45 deg. according to the coordinate system shown in Fig. 2.

The second composite panel was a monolithic laminate panel composed of 4 plies with stacking sequence [+45°/-45°/-45°/+45°] according to the coordinate system shown in Fig. 3. The panel was made of EHG250-68-50 prepreg with glass fabric reinforcement (8H satin, 296 g/m^2) and epoxy resin. Material properties are given in Tab. 1 and Tab. 2 [4].

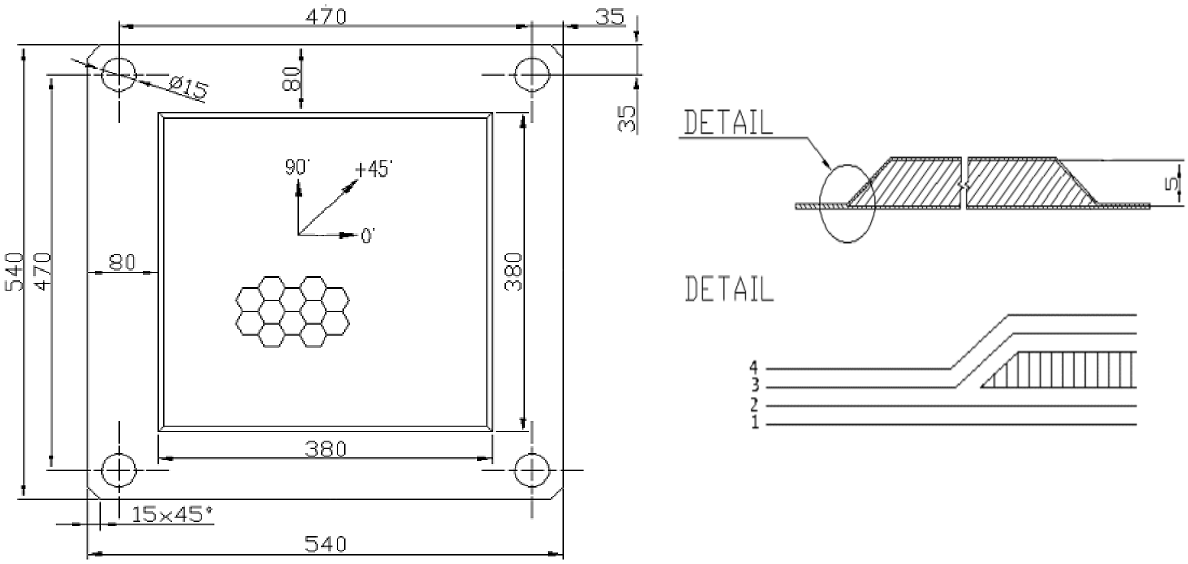

Fig. 2: Tested sandwich panel [4]

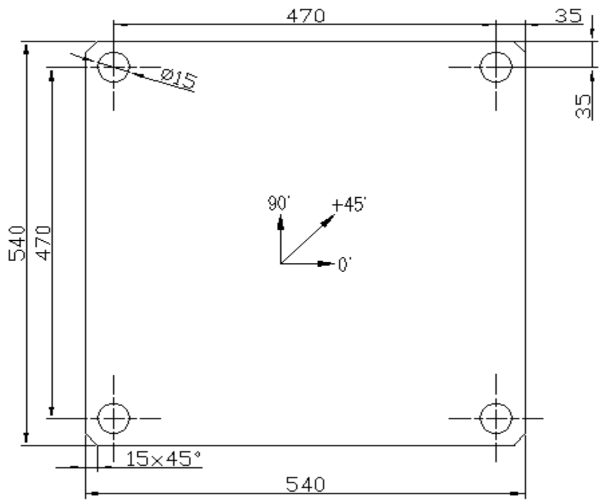

Fig. 3: Tested monolithic laminate panel [4]

	Units	EHG250-68-50	EP121-C20-45
Longitudinal Tensile Modulus $\mathbf{E_L}$	[GPa]	23.5	41.8
Transverse Tensile Modulus $\mathbf{E_T}$	[GPa]	20.5	41.7
Poisson´s Ratio $\boldsymbol{\nu_{LT}}$	[-]	0.15	0.05
In-plane Shear Modulus $\mathbf{G_{LT}}$	[GPa]	4.2	4.8

Tab. 1: Material properties of prepreg EHG250-68-50 and EP121-C20-45 [4]

	Units	Nomex ECA-3.2-29
Compression Modulus	[MPa]	138
Compression Strength	[MPa]	2.1
Shear Modulus, L-direction $\mathbf{G_L}$	[MPa]	48
Shear Strength $\boldsymbol{\tau_L}$	[MPa]	1.32
Shear Modulus, W-direction $\mathbf{G_W}$	[MPa]	30
Shear Strength $\boldsymbol{\tau_W}$	[MPa]	0.73

Tab. 2: Material properties of honeycomb Nomex ECA-3.2-29 [4]

FEM analyses

Models were prepared and evaluated in Femap software. Analyses were performed using Nastran solver. The sandwich panel was modelled by 2 different approaches. In the first case (Fig. 4), the panel was meshed only by 2D laminate type elements (skins and core, both using 2D orthotropic material models), while in the second case (Fig. 4) the panel was meshed by a combination of 2D laminate type elements (skins, using 2D orthotropic material model) and 3D solid elements (core, using 3D isotropic continuum model). The monolithic laminate plate (Fig. 5) was modelled by 2D laminate type elements only (using 2D orthotropic material model). The effect of the fixture frame was represented by 1D beam elements at the edges of the panels in all three cases. Fig. 6 shows a detailed representation of 1D elements. Fig. 7 shows a detailed representation of the arrangement of the sandwich models.

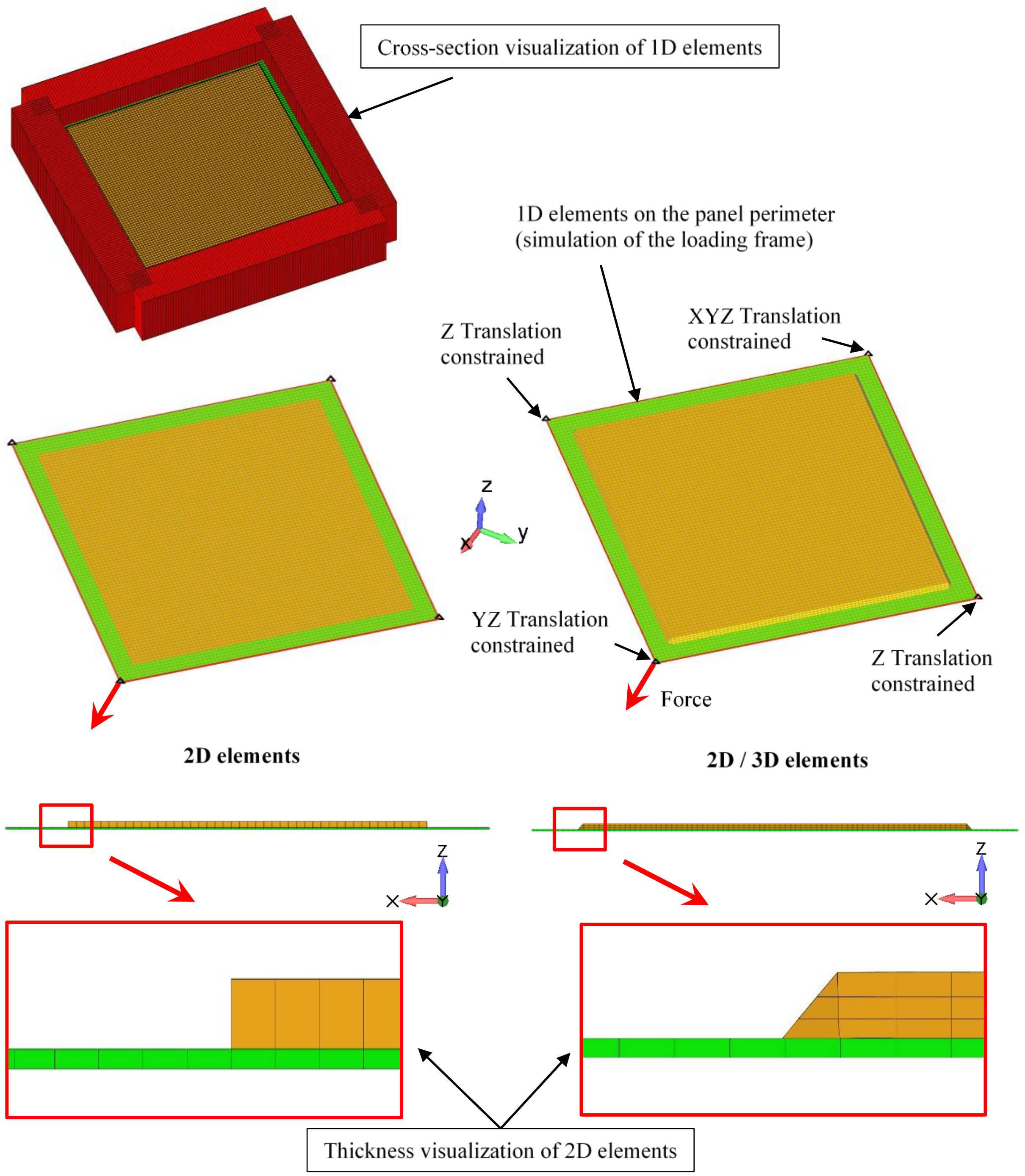

Fig. 4: FE models of sandwich panel

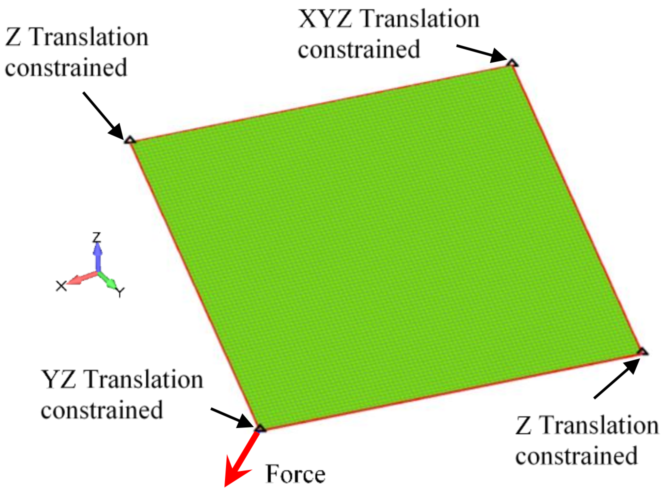

Fig. 5: FE model of monolithic laminate panel

The 2D model of sandwich panel was made of 7 396 2D layered shell elements and 344 1D beam elements. The 3D model of sandwich panel contained 17 328 3D solid elements, 13 776 2D laminate type elements and 344 1D beam elements. The model of monolithic laminate panel consisted of 7 396 2D laminate type elements and 344 1D beam elements.

The all three FE model configurations were validated and verified by standard geometry and numerical checks. In addition, the necessary FEM mesh density was verified to obtain reliable results. The models were verified by adjusting the element size when solving the linear buckling. In all three model configurations, 15 elements were selected as the initial number of elements on the edge of the panel. The number of elements on the edge of the panels was gradually increased to 60 for the monolithic and the 2D sandwich panel and 90 for the 3D sandwich panel. With a further increasing in the number of elements, the value of the critical force did not change. Therefore, FE mesh density with 60 elements on the edge of the panel for the monolithic and the 2D sandwich panel and 90 elements on the edge of the panel for the 3D sandwich panel were used in the FEM models.

Results of analyses

First, a linear solution was performed for all the 3 cases mentioned in the previous paragraphs. The critical force for the sandwich panel created only by 2D elements was 38 102 N, while for the panel created by a combination of 2D and 3D elements it was 33 085 N. The critical force of the monolithic laminate panel was 1 662 N. The analyses also included a determination of eigenshapes gained by the linear buckling solution (Fig. 8 and Fig. 9) to validate analysis by experimental data.

The next step was to modify computational models by geometrical imperfections. The initial geometrical imperfections of the original planar panels were modified by induced deflection in the middle of the panel. Four different deflection sizes (0.25 mm, 0.50 mm, 0.75 mm and 1.00 mm) were used to determine their effect on the critical force value. The critical force for all 3 model types were obtained by a nonlinear solution. The critical force for the sandwich panel created only by 2D elements was on average (from imperfection deflection sizes) 35 719 N, while for the panel created by a combination of 2D and 3D elements it was 21 780 N. The critical force of the monolithic laminate panel dropped on average to 1 605 N, where it loses stability, but does not come to collapse.

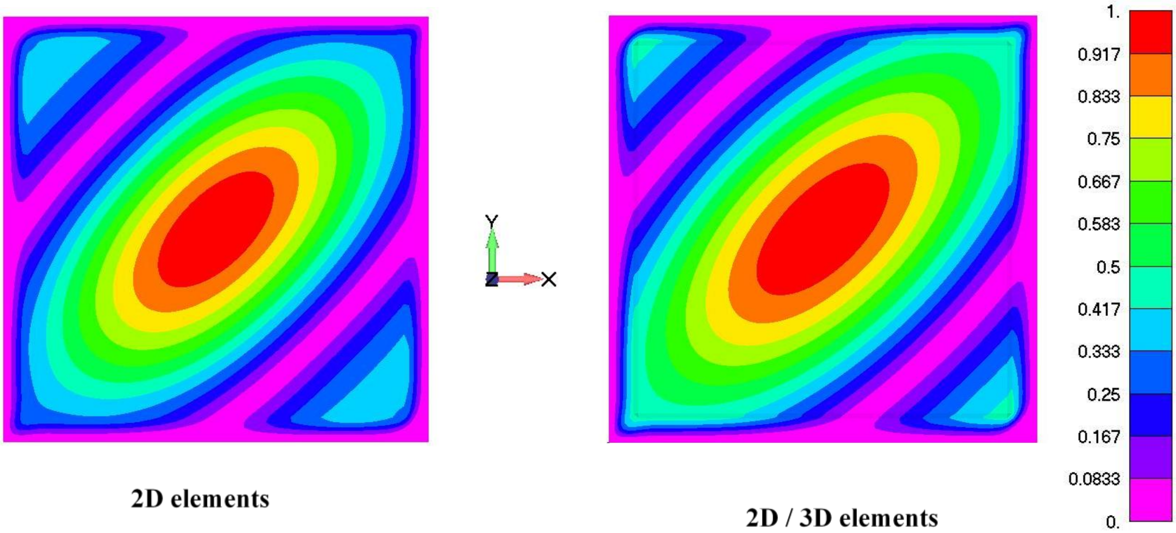

Fig. 8: The first eigenshape of the sandwich panel

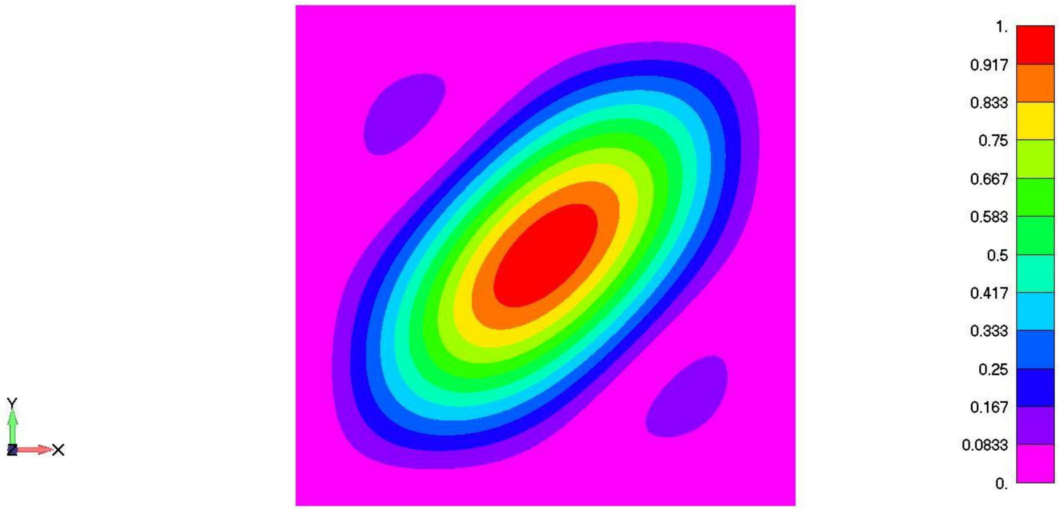

Fig. 9: The first eigenshape of the monolithic laminate panel

Experimental measurements

An example of test set-up is shown in Fig. 10 (left). The tests were performed in VZLU. A tested panel was clamped in the test fixture (frame) by bolts on its perimeter. The test fixture consists of four pinned arms. The frame was loaded by tensile force acting in the diagonal direction. The loading was performed by the Hydropuls servohydraulic system with a maximum loading force of 100 kN.

The considered tested area of the panel has dimensions 400 × 400 mm section of the panel. The remainder area of the panel was designed to transfer loads between the fixture and the tested area. The loss of panel stability was evaluated based on load – displacement curve and also by using the Aramis HS system that enable optical measurement of 3D displacements. The measurement section of the panel (panel area with foil) is shown in Fig. 10 (right). The output of this measuring device was a displacement map [4].

Fig. 10: The test set-up (left) and the measurement section (right) [4]

Discussion of results

An overview of the sandwich panels results for both approaches is shown in Fig. 11. The values of the critical forces show a considerable difference even before the imperfections were applied. The critical force for the sandwich panel created only by 2D elements was 38 102 N, while for the panel created by a combination of 2D and 3D elements 33 085 N. In the experimental part, the value of the sandwich panel critical force was set at 22 000 N. The difference in both computational approaches increases even more with the application of imperfections. The critical force for the sandwich panel created only by 2D elements was on average (from all imperfection sizes) 35 719 N, while for the panel created by a combination of 2D and 3D elements 21 780 N. As can be expected, increasing size of imperfection decreasing the value of the critical force.

Fig. 12 shows an overview of the monolithic laminate panels results. It shows a rather good agreement in computational and experimental values. However, regarding the experimental results, it is important to mention that the accurate determination of the monolithic laminate panel critical force was more less estimation. The monolithic exhibits loss of stability practically from the beginning of loading. The value of the critical force was determined on approximately 1 500 N based on more significant change in slope of load-displacement curve. Fig. 12 further shows that for small sizes of imperfections (from 0.25 mm to 1.00 mm) the critical force values remain almost constant compare to sandwich panel. This fact evokes that the size of the imperfection has a greater effect on the critical force of the sandwich panels than on the monolithic panels, but it is not in line with common response of this type of structures. Usually stiffer panels are less sensitive to initial imperfections. The reasons of this behaviour will be the ability of the models to simulate real response of the panels and also uncertainty in behaviour of thin low stiffness structures where any irregularity in the structure (geometrical, internal arrangement, …) can cause large deviations.

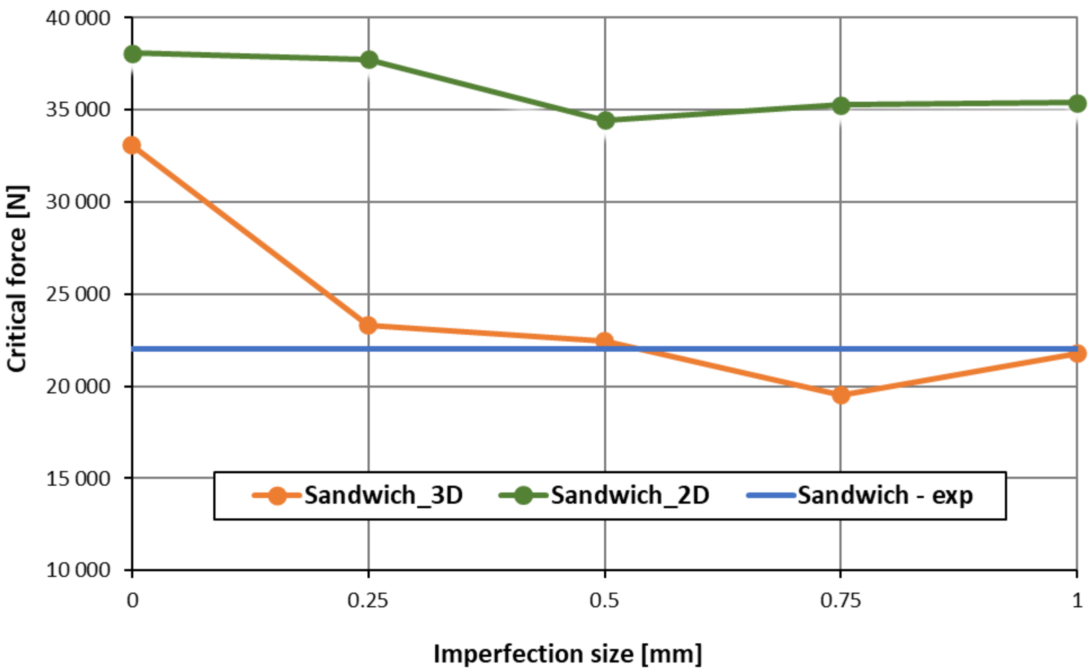

Fig. 11: Dependency of critical force on imperfections size – sandwich panel

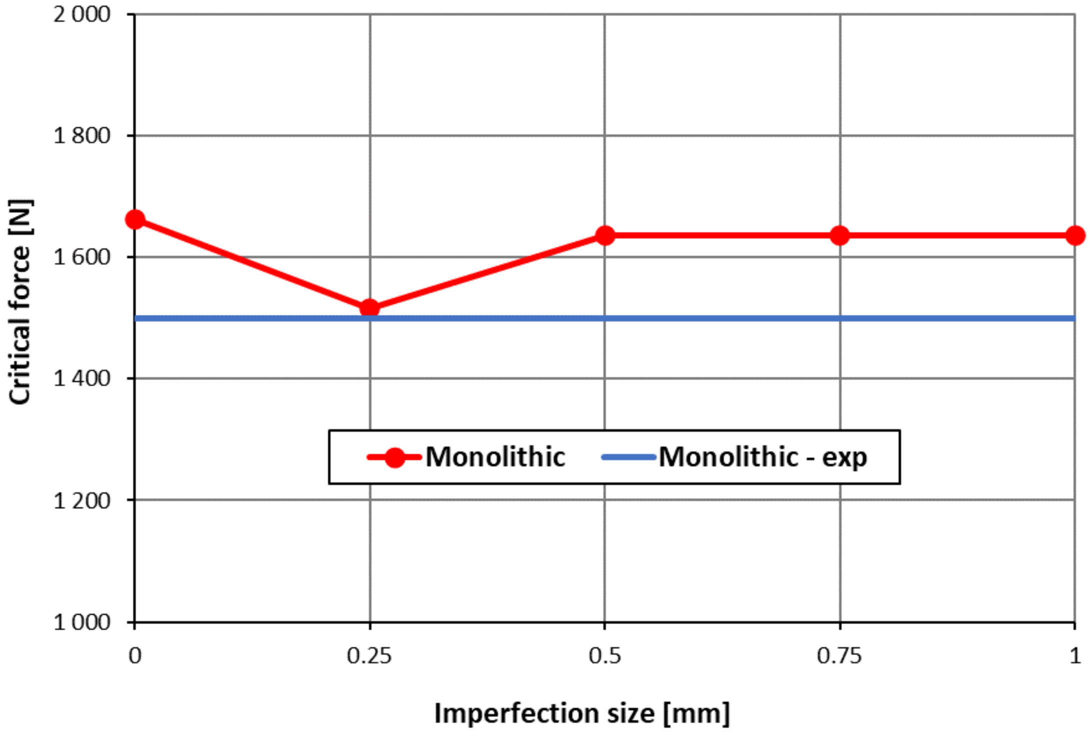

Fig. 12: Dependency of critical force on imperfections size – monolithic panel

Conclusions

From the obtained results it is clear that neglecting the influence of even relatively small geometric imperfections can lead to relatively large errors in simulations of their behaviour. This behaviour is even important for relatively stiff structures like sandwich panels (decreasing about 30% between planar and 0.25 mm deflected sandwich panel). Another interesting result is also a comparison of 2D and 3D models of sandwich structures. The 2D model of sandwich structure is sufficient for linear static analysis but for nonlinear simulations exhibits significantly higher critical force (up to 60%) than 3D model what could be very danger in real structures.

Thus, it is obvious that experimental testing still plays a very important role in the development and the validation of numerical models as well as consideration of possible structural irregularities including geometrical imperfections.

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References

[1] M. Baumruk (2007). Mechanics of composite materials, analytical methods for calculation of stability problems of composite plates and sandwich panels and their comparison with FEM, *Report*, Czech technical university in Prague, Faculty of Mechanical Engineering, Aerospace Research Centre, Prague.

[2] B.H. Sun, K.Y. Yeh, F.P.J. Rimrott (1995). On the Buckling of Structures, *Technische Mechanik*, Vol. 15, No. 2, Pp. 129-140.
Retrieved September 18, 2020 from:
http://www15.ovgu.de/ifme/zeitschrift_tm/1995_Heft2/Sun_Yeh.pdf

[3] P. Bala, A.V. Raviprakash, V. Ananthapathmanaban (2010). Parametric study on buckling behaviour of thin stainless steel cylindrical shells for circular dent dimensional variations under uniform axial compression, *International Journal of Engineering, Science and Technology*, Vol. 2, No. 4, Pp. 134-149.
Retrieved September 18, 2020 from:
https://pdfs.semanticscholar.org/3f54/1846ba61f0e70048254c6c667663902fa346.pdf?_ga=2.180015012.1825113141.1600435050-136078452.1599031507

[4] P. Průcha (2013). Properties of composite elements used in aircraft primary structures, *Doctoral dissertation*, Czech technical university in Prague, Faculty of Mechanical Engineering, Department of Aerospace Engineering, Prague.

[5] T. Abbey (2015). Linear and Nonlinear Buckling in FEA, *Digital Engineering 247*. Retrieved April 20, 2020 from:
https://www.digitalengineering247.com/article/linear-and-nonlinear-buckling-in-fea/