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SHEAR BUCKLING BEHAVIOUR OF THE DOUBLE DELAMINATED SHIP DECK PLATES

Ionel CHIRICA[1], Elena-Felicia BEZNEA[1], David HUI[2]

[1] University Dunarea de Jos of Galati, ROMANIA
[2] University of New Orleans, USA
ionel.chirica@ugal.ro

ABSTRACT

The work presented in this paper analyzes the influence of the imperfections, such as double delaminations, on the changes in the shear buckling behaviour of the ship deck plates made of composite materials. Thus, parametric analysis of the postbuckling behaviour of composite plates with double delaminations are treated. The orthotropic delamination model, describing the delaminating process, is applied. The damaged part of the structures and the undamaged part have been represented by well-known finite elements (layered shell elements). The influence of the position and the ellipse's diameters ratio of the delaminated zone on the critical buckling force are investigated. The plates are made of E-glass polyester, having the dimensions: 320 mm x 320 mm and a thickness of 5.12 mm. The numerical analysis is done using COSMOS/M soft package.

Keywords: shear buckling, delaminations, composite plates

1. INTRODUCTION

Composite panels are generic structural elements in the sensitive structural weight for the marine applications. Laminated composite panels, which are anisotropic, are gaining popularity in the structural applications, such as ship hulls, decks, ship and offshore superstructures. These panels are increasingly used in the structural marine applications due to their high specific stiffness and specific strength [1]. The use of laminated composites provides the flexibility to tailor different properties of the structural elements in order to achieve the stiffness and strength characteristics. These panels, unfortunately, have one important characteristic connected to the big sensitivity on the geometrical and mechanical imperfections (different dimensions as compared to the design ones). Another kind of imperfections is referred to the material [2, 3]. Taking into account that the fabrication technologies of the composite materials are hand made based, the probabilistic occurrence of defects is quite too high.

These defects are of following types: the directions of fibers are different of the designed ones, variations in thickness, inclusions, initial transversal deformations [4].

The delamination reduces the elastic buckling load of the laminated composite structures and leads to the global structural failure at loads below the design level. Therefore, the problem of the buckling of the delaminated composite structures has generated significant research interest and has been the subject of many theoretical and experimental investigations. However, questions still remain regarding a complete understanding and details of the phenomena involved.

The ship structure plates are subjected to any combination of in plane, out of plane and shear loads during exploitation. Due to the geometry and the general load of the ship hull, buckling is one of the most important failure criteria. The buckling failure mode of a stiffened plate can further be subdivided into global buckling, local skin buckling and stiffener crippling. The global buckling is the collapse of the whole structure (the collapse of the stiffeners and the shell as one unit). On the other hand, the local plate buckling and the stiffeners crippling are localized failure modes involving only a local failure of the skin in the first case and the stiffener in the second case. A grid stiffened panel will fail in any of these failure modes depending on the stiffeners, the plate thickness, the shell winding angle and the type of the applied load.

Understanding the delamination is essential for preventing the catastrophic failures. Therefore, the analysis of the delamination behavior as obtained from test data, the modelling delamination, the analysis of the structural performance under delamination and the prevention and the mitigation of the delamination are the main aim of the research team that performed this work.

In [5], the buckling behaviour of the laminated panels with one stiffener, subjected to compression using a layer wise finite element formulation, is presented. Nemeth have done some parametric studies based on the orthotropic plate theory and produced generic buckling design charts in terms of useful nondimensional parameters for unstiffened composite panels subjected to different loadings [6, 7]. In [8], some parametric were studied the simply supported laminated composite blade-stiffened panels subjected to in-plane shear loading. Several important parameters influencing the buckling behaviour are identified and guidelines are developed.

The buckling behaviour of the multiple delaminated plates subjected to shear and compression loading has been studied in [9, 10, 11, 12] by means of the finite element analysis. The studies show several trends in the effect of number positions on the surface and through-the-thickness position of the delaminations upon the buckling response. These findings could be used for evaluating the reliability of the laminate structures, which might be subjected to impact loading, such as the ship hull structures.

This paper addresses the effects of the delaminations on the shear buckling and postbuckling behaviour of the rectangular plates made of advanced composite materials. An overview of a past research is presented and several key findings and behavioral characteristics are discussed. The analysis includes the effects of the delaminations' positions, the loading and the boundary conditions, the results of the numerical and experimental tests. Some overall important findings of these studies are that the plates that have delaminations can buckle at loads higher than the buckling loads for the corresponding perfect plates and they can exhibit substantial postbuckling load-carrying capability.

The presence of in-plane loading may cause buckling of the stiffened panels. An accurate knowledge of the critical buckling load and the mode shapes are essential for a reliable and lightweight structural design.

If an initial delamination exists, this delamination may close under the applied load. To prevent the two adjacent plies from penetrating, a numerical contact model is used.

2. THEORY OF SHEAR BUCKLING ORTHOTROPIC PLATES

The buckling analysis of a plate may be divided into three parts: classical buckling analysis, difficult classical effects and non-classical phenomena. The classical buckling analysis is a generalization of the Euler buckling for beams.

The awkward effects in the classical buckling analysis are in connection with the vibrations, the shear deformations, the prings, the non-homogeneities and the variable thicknesses, the nonlinear relations between stresses and strains. The non-classical buckling analysis involves considerations such as imperfections, non-elastic behaviour of the material, dynamic effects of the loading, the fact that the in-plane loading is not in the initial point of the plate.

Finally, one have to remark that no plate is initially perfect and if the initial deviation (concerning the flatness or the symmetry) exists, no clear buckling phenomenon may be identifying. The deviations of the plate from the flatness and the symmetry are usually called imperfections (initial transversal imperfections, delaminations) as it will be treated in the following chapters of this study.

The state of equilibrium of a plate deformed by forces acting in the plane of the middle surface is unique and the equilibrium is stable if the forces are sufficiently small. If, while maintaining the distribution of forces constant at the edge of the plate, the forces are increased in magnitude, there may arise a time when the basic form of equilibrium ceases to be unique and stable and other forms become possible, which are characterized by the curvatures of the middle surface.

When the plates are subjected to the application of large in-plane loads, either compressive or shear, they buckle. The phenomenon of buckling is a non-linear one, which is characterized by a disproportionate increase of the displacements associated with the small increments of the loads. The methodology for determining and analyzing the buckling behaviour of the laminated composite plates is, in essence, identical to that applied to the isotropic plates. As in isotropic plates, it involves the solution of an eigen-value problem associated with a governing set of homogeneous differential equations and a prescribed set of homogeneous boundary conditions.

In the case of the isotropic plates, exact buckling solutions are available only for a few combinations of loading and boundary conditions.

The theory and the differential equation of bending for the anisotropic plates were established by Huber and the governing differential equation for shear buckling of a general orthotropic plate is

$$D_{11}\frac{\partial^4 w}{\partial x^4}+2D_{33}\frac{\partial^4 w}{\partial x^2\partial y^2}+D_{22}\frac{\partial^4 w}{\partial y^4}+2N_{xy}\frac{\partial^2 w}{\partial x\partial y}+4D_{13}\frac{\partial^4 w}{\partial x^3\partial y}+4D_{23}\frac{\partial^4 w}{\partial x\partial y^3}=0 \tag{1}$$

where D_{11}, D_{22}, D_{33}, D_{13}, D_{23} are the orthotropic plate stiffnesses, calculated according to the equation

$$D_{ij}=\sum_{k=1}^{N}\overline{Q}_{ij}^{k}\left(z_k^3-z_{k-1}^3\right)/3\,. \tag{2}$$

where $\overline{Q}_{ij}^{k}$ is the rigidity coefficient from the Hooke's law written for the k-th ply.

The thickness and position of every ply can be calculated from the equation

$$t_k=z_k-z_{k-1}\,, \tag{3}$$

and

$$\overline{z}_k=z_{k-1}+t_k/2\,. \tag{4}$$

The last two terms from the equation (1) are the measure of the orthotropic coupling, resulting from the fact that the principal orthotropic axes are not orthogonal to the plate geometry axes.

A special orthotropic plate, $D_{13}=D_{23}=0$ is a case which has received the most attention by the researchers. The problem of the stability of the orthotropic plates caused by shear was apparently first examined by Bergmann and Reissner [10], who considered it an infinitely long in the *x* direction and they also neglected the bending stiffness in that direction. The governing differential equation used was:

$$2D_{33}\frac{\partial^4 w}{\partial x^2 \partial y^2} + D_{22}\frac{\partial^4 w}{\partial y^4} + 2N_{xy}\frac{\partial^2 w}{\partial x \partial y} = 0 \tag{5}$$

Approximate solutions are obtained for the buckling of the clamped edged finite plates, using the Rayleigh-Ritz method in [11].

For solving geometrical and material nonlinear problems, the load is applied as a sequence of sufficiently small increments so that the structure can be assumed to respond linearly during each increment.

For each increment of load, increments of displacements and corresponding increments of stress and strain are computed. These incremental quantities are used to compute various corrective stiffness matrices (variously termed geometrics, initial stress and initial strain matrices), which serve to take into account the deformed geometry of the structure. A subsequent increment of the load is applied and the process is continued until the desired number of load increments have been applied. The net effect is to solve a sequence of the linear problems wherein the stiffness properties are recomputed based on the current geometry prior to each load increment. The solution procedure takes the following mathematical form:

$$(K + K_I)_{i-1}\Delta d_i = \Delta Q \tag{6}$$

where K is the linear stiffness matrix, K_I is an incremental stiffness matrix based upon displacements at load step i-1, Δdi is the increment of displacement due to the i–th load increment, ΔQ is the increment of load applied.

The plate material is damaged according to a specific criterion.

The buckling load determination may use the Tsai-Wu failure criterion if the general buckling does not occur till the first-ply failure occurring. In this case, the buckling load is considered as the in-plane load corresponding to the first-ply failure occurring.

The failure criterion is used to calculate a failure index (F.I.) from the computed stresses and user-supplied material strengths.

The failure index is calculated in each ply of each element. In the ply where failure index is

$$F.I. > 1 \tag{7}$$

the first-ply failure occurs, according to the Tsai-Wu criterion. In the next steps, the tensile and compressive properties of this element are reduced by the failure index. If the buckling did not appear until the moment of the first-ply failure is occurring, the in-plane load corresponding to this moment is considered as the buckling load.

Three types of failure status are determined in each layer of each element:

- OK

$$F.\ I. < 1 \tag{8}$$

- FAIL 1 in the case:

$$|\sigma_1| < R_1^T \text{ and } |\sigma_1| < R_1^C \tag{9}$$

- FAIL 2 in the case:

$$|\sigma_1| \geq R_1^T \text{ and } |\sigma_1| \geq R_1^C \tag{10}$$

3 NUMERICAL ANALYSIS OF COMPOSITE PLATES SHEAR BUCKLING

The numerical analysis was carried out using a licenced finite element package software COSMOS/M. For the present study, a 3-D model with 3-node SHELL3L composite element of COSMOS/M is used (Fig. 2). In the area of the delamination, the panel is divided into two sub-laminates by a hypothetical plane containing the delamination. The delamination model has been developed by using the surface-to-surface contact option.

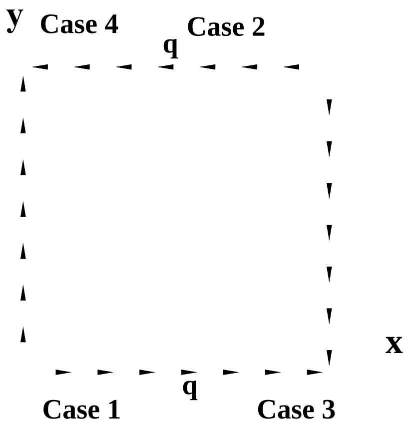

Fig. 1. Positions of double delamination in the plate

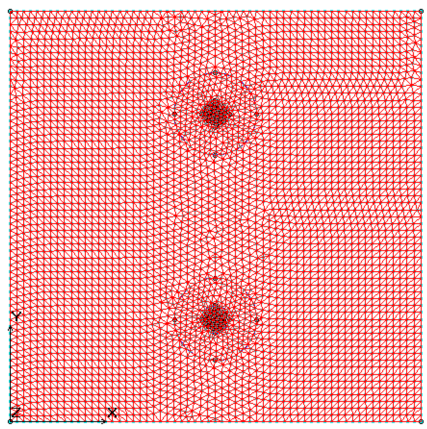
Fig. 2. Plate mesh in the Case 1

In COSMOS/M, the delaminated regions were modelled by two layers of elements with coincident, but separate nodes. The direction of the tangential loading is considered along the plate sides.

As it is seen in Figure 1, four cases of double delaminated plate are studied in this paper.

The shape of each delamination is considered as circular, each one having the diameter of 20 mm. For each case, the various positions of the double delamination in the stack are considered. For the same position, the delaminations are placed between the same layers, according to Table 2. In Figure 2, an example of plate mesh is presented.

The square plates (320 mm x320 mm) are made of E-glass/polyester concerning 16 biaxial layers having the orthotropic directions and a thickness (4.96 mm) according to the Table 1. The topological code of the plate is $[0_2/45/90_2/45/0_2]_s$. The material characteristics, as determined in experimental tests (using stretching machine and strain gauges), are:

E_x=38.6 GPa, E_y=8.27 GPa, E_z=8.27 GPa,

G_{xy}=4.14 GPa, G_{xz}=4.14 GPa, G_{yz} = 4.6 GPa;

μ_{xy}=0.3, μ_{yz}=0.42, μ_{xz}=0.3;

R_x^T=1.062 GPa, R_x^C=0.610 GPa, R_y^T=0.031 GPa, R_y^C=0.118 GPa, R_{xy}=0.72 GPa.

For the same case of a double delaminated plate, the delaminations are considered to be placed in the same plane, between two neighbor macro-layers (ML), as it is presented in Table 2. A macro-layer is a group of layers having the same characteristics (direction of fibers versus direction of axial compression). Due to the position in the stack of the layers, a number of 10 macro-layers can be considered, as is presented in Table 1. Taking into consideration that there are 10 macro-layers, only the positions placed between two neighbours macro-layers, from 1 to 6, respectively, are studies.

Table 1. Composite stack

Macro-layer No.	Number of layers	Fiber direction [°]	Thick-ness [mm]
1	2	0	0.62
2	1	45	0.31
3	2	90	0.62
4	1	45	0.31
5	2	0	0.62
6	2	0	0.62
7	1	45	0.31
8	2	90	0.62
9	1	45	0.31
10	2	0	0.62

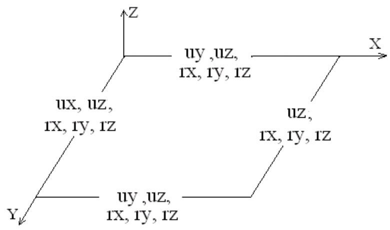

Fig. 3. Boundary conditions

Table 2. Position of delaminations in all 4 cases of double delaminations

Macro-layer No.	Case a	Case b	Case c	Case d	Case e
1	1 ML				
2	9 ML	2 ML			
3		8 ML	3 ML		
4			7 ML	4 ML	5 ML
5				6 ML	
6					5 ML
7					
8					
9					
10					

The boundary conditions, shown in Fig. 3 (where the corresponding d.o.f., denoted with u for the displacement and r for the rotation, are considered to be equal to zero) are described on the plate sides.

On the outline of the delaminated area, the continuity condition for the displacements is imposed.

Initially, both sublaminate plates are considered to be in contact. Between the delaminated layers, the contact finite elements (GAP elements) are used.

The loading was considered to be a shear force (q), acting on the plate sides as it is shown in Fig. 1.

For all cases, in the non-linear calculus, one layer damaged on the same type of loading independent of the position of the delaminations on the stack and on the plate. The buckling load is 17.5 MPa, for all cases. The type of fail is Fail 1.

The values of the ultimate strength (the buckling load) were determined by Tsai-Wu criterion for all double delaminated plates.

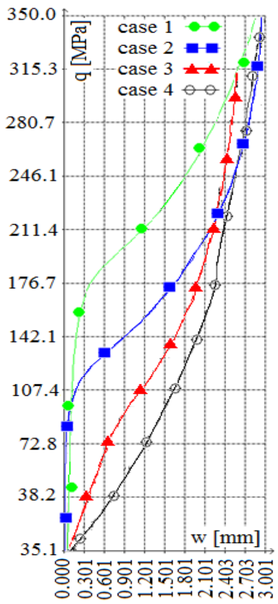

Fig. 4. Variations of q versus w,for the case of delaminations placed between layers 1 and 2 (Cases 1-a, 2-a, 3-a, 4-a). Buckling load: 46 MPa < q_{cr} < 156 MPa

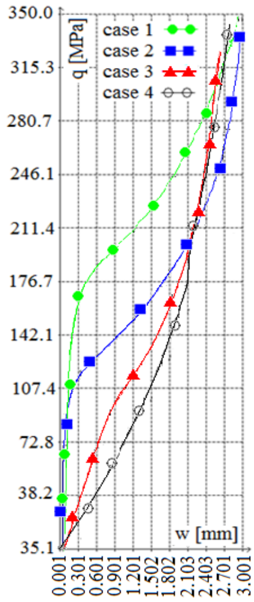

Fig. 5. Variations of q versus w, for the case of delaminations placed between layers 2 and 3 (Cases 1-b, 2-b, 3-b, 4-b). Buckling load: 49 MPa < q_{cr} < 157 MPa

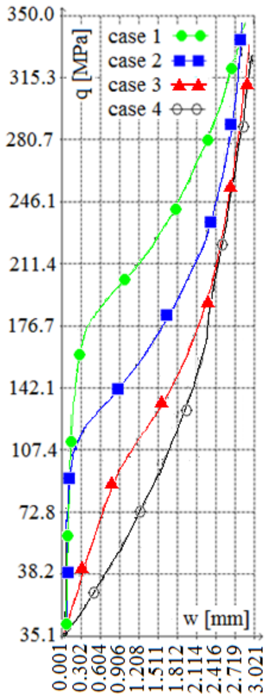

Fig. 6. Variations of q versus w, for the case of delaminations placed between layers 3 and 4 (Cases 1-c, 2-c, 3-c, 4-c). Buckling load: 44 MPa < q_{cr} < 156 MPa

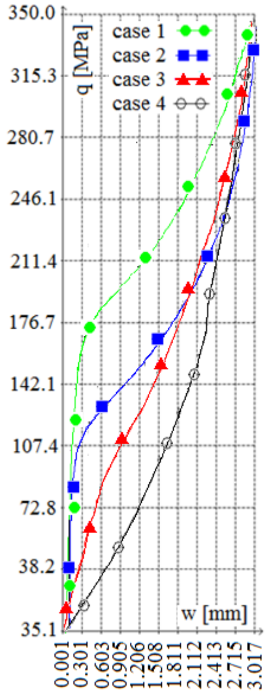

Fig. 7. Variations of q versus w, for the case of delaminations placed between layers 4 and 5 (Cases 1-d, 2-d, 3-d, 4-d). Buckling load: 39 MPa < q_{cr} < 155 MPa

It is possible to generate simultaneously other failures types. For the ultimate strength, only the first failure occurred in the layers, is interested. This ultimate strength can be in the form of tensile or compression stress.

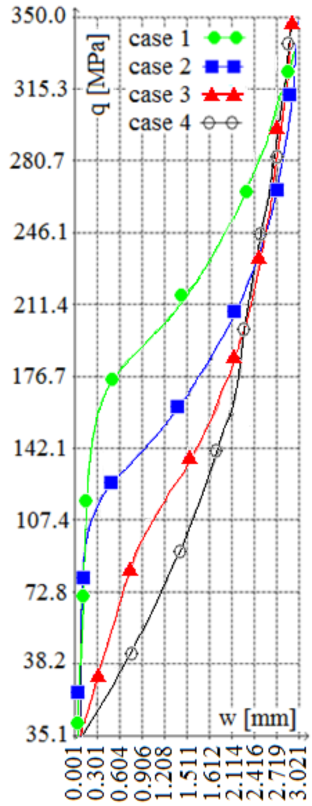

Fig. 8. Variations of q versus w, for the case of delaminations placed between layers 5 and 6 (Cases 1-e, 2-e, 3-e, 4-e). Buckling load: 44 MPa< q_{cr} <156 MPa

4. DISCUSSION AND CONCLUSIONS

The results obtained from the analysis of the numerical results, allow for reaching certain conclusions related to the behaviour of the double delaminated composite plate under shear loads.

From this comparative analysis, it can be concluded that the numerical model provides a good approximation to the actual behaviour of the delaminated plates. Thus, it can be used as an useful analysis tool in order to develop and establish new design rules for the composite ship structures loaded by the impact forces producing delaminates.

Moreover, the phenomenon study requires a stress analysis in order to improve the evaluation of the structural response of the delaminated plate. The plate is subjected to a shear stress state in the presence of a non-linear material and two delaminations placed in various positions. A detailed analysis of the tested plates was conducted and different responses were detected. Figures 4-8 represents, in terms of deflection and stress evolution in the middle point of the panel, these different structural responses.

An important conclusion reached during this work was the importance of the residual stress of the delaminated plates. Also, the comparative analysis has enabled to confirm the behaviour of multiple delaminated plates under shear load.

In the tested plates, a tension field band was developed as a new resistant mechanism after reaching the buckling load level, but this behaviour is clearly influenced by the material non-linearity.

The results obtained by numerical tests have been also used in order to set up suitable numerical models able to interpret correctly the response of the delaminated composite plates.

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REFERENCES

[1] **Altenbach, H., Altenbach, J. & Kissing, W.**, 2004,. Mechanics of Composite Structural Elements, Ed. Springer, Berlin.

[2] **Adams, D.F., Carlsson, L.A. & Pipes, R.B.**, 2003, Experimental Characterization of Advanced Composite materials, Ed. Taylor & Francis Group.

[3] **Jones, R.M**., 1999, Mechanics of Composite Materials, Ed. Taylor & Francis Group, London.

[4] **Thurley, G.J., Marshall, I.H.**, 1995, Buckling and Postbuckling of Composite Plates, Ed. Chapman & Hall, London.

[5] **Huo, M.V., Harik, I.E., Ren, W.X.,** 2002, Buckling behaviour of stiffened plates, Int. J. Solids Struct, 39, 30, pp. 39-55.

[6] **Nemeth, M.P.,** 1992, Buckling behaviour of long symmetrically laminated plates subjected to combined loadings, TP 3195, NASA.

[7] **Nemeth, M.P**., 1997, Buckling behaviour of long symmetrically laminated plates subjected to shear and linearly varying axial edge loads, TP 3659, NASA.

[8] **Mallela,K.U., Upadhyay, A.,** 2006,. Buckling of laminated composite stiffened panels subjected to in-plane shear: A parametric study. Thin-Walled Structures 44, pp. 354-361.

[9] **F. Cappello, D. Tumino**, Composites Science and Technology, Experimental Techniques and Design in Composite Materials 66 (2) (2006) 264-272.

[10] **H. Huang, G.A. Kardomateas**, Buckling of Orthotropic Beam-Plates With Multiple Central Delaminations, Int. J. Solids Structures 35 (13) (1998) 1355-1362.

[11] **S.F. Hwang, G.H. Liu**, Buckling behavior of composite laminates with multiple delaminations under uniaxial compression,Composite Structures 53 (2) (2001) 235-243.

[12] **D.Y. Park, S.Y. Chang, S.S. Yhim**, Elastic buckling analysis of laminated composite plates with through-the-width delamination using EAS solid element, KSCE Journal of Civil Engineering 10 (6) (2006) 17-30.

[13] **Smith, R.C.T.,** 1946, The buckling of plywood plates in shear, Australian C.S.I.R. Aero. Res.Labs. (Melbourne) Rep. SM 51.

[14] **F. Stan, A.V. Munteanu, C. Fetecau**, 2011, Rev Mat Plast 48 (1) (2011) 1-6.

[15] **Travesa, A.T.,** 2006, Simulation of Delamination in Composites under Quasi-static and Fatigue Loading using Cohesive Zone Models, Doctoral Thesis, Universidad de Girona.

[16] **Knight N. F. Jr. & Starnes J. H. Jr**., 1988, Postbuckling Behavior of Selected Curved Stiffened Graphite Epoxy Panels Loaded in Axial Compression, AIAA Journal, Vol. 26, No. 3, pp.344-352.

[17] **Naganarayana, B.P. & Atluri, S.N.,** 1995, Strength Reduction and Delamination Growth in Thin and Thick Composite Plates under Compressive Loading, Computational Mechanics, 16: 170-189.

[18] **Pietropaoli, E., Riccio, A. & Zarrelli, M.**, 2008, Delamination Growth and Fibre/Matrix Progresive Damage in Composite Plates under Compression. ECCM13, The 13-th European Conference on Composite Materials, June 2-5, Stockholm, Sweden.

[19] **Schlack, A.L., Jr.**, 1964, Elastic Stability of Pierced Square Plates. Experimental Mechanics, June 167–172.

[20] **Thurley, G.J. & Marshall, I.H.**,1995, Buckling and Postbuckling of Composite Plates, Ed. Chapman & Hall, London.