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Tomas Grahn

Aeronautics Division, FFA
SE-17290 Stockholm
Sweden

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Report title

Effects of geometrical imperfections on postbuckling behaviour of delaminated composite plates

Abstract (not more than 200 words)

This paper investigates how geometrical imperfections, which in most cases are present for impacted laminates, affect the postbuckling behaviour of delaminated composite plates under compression. Delaminations are one of the most frequently appearing material damage due to impact. The influence of different shapes of the geometrical imperfections on the response has been studied. The program system DEBUGS, which is developed and specialized to simulate delamination buckling and growth, is used for the analyses. DEBUGS is based on the finite element program ADINA. It is found that the geometrical imperfections influence the buckling behaviour, and thus also possibly the initiation of delamination growth. A more accurate model of delamination buckling of impact damaged laminated composites should thus include a feature where the initial shape of the composite may be varied, e.g. in a model where the material degradation in the impact damaged zone is modelled.

Keywords

Buckling, imperfection, composite laminate, delamination, finite element

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Rapportens titel (i översättning)

Inverkan av geometriska imperfektioner på postbuckling i kompositplattor med delamineringar

Sammanfattning (högst 200 ord)

I denna rapport undersöks hur en geometrisk imperfektion, som oftast förekommer efter att ett kompositlaminat har utsatts för någon typ av slag, påverkar postbucklingsresponsen av kompositlaminat med delamineringar under tryckbelastning. Delamineringar är en av de vanligast förekommande defekterna vid slagskador. Inverkan lav olika sorters geometriska imperfektioner på responsen har studerats. För detta ändamål har programmet DEBUGS använts. DEBUGS är utvecklat för att simulera delamineringsbuckling och delamineringstillväxt och programmet är baserat på det det finita element programmet ADINA.. I analyserna har det framkommit att de geometriska imperfektionerna har inverkan på bucklingsbeteendet, och därigenom också rimligtvis på initieringen av delamineringstillväxt. Följaktligen borde en mer utförlig modell av delamineringsbuckling vid slagskador inkludera möjligheten att variera hur initialgeometrin ser ut, t.ex. i en modell där man tar hänsyn till den nedsatta styvheten i det slagskadade området.

Nyckelord

Buckling, imperfektion, kompositlaminat, delaminering, finita element

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Contents

1. Introduction

Composites with high-modulus fibres (e.g. boron or carbon) have been widely used in aerospace applications due to their high strength/weight ratios. A major concern in the design of aircraft structures of composite laminates, however, is impact damage, since such damage may severely reduce the strength and stability of the structure [1]. A typical impact damage zone contains matrix cracks within plies and normally multiple delaminations between plies through the thickness of the laminate. More extensive, high-energy impact damage may also result in fibre fracture, which naturally severely reduces the strength of the laminate. An impact of some kind may also introduce a dent in the laminate on the impacted side, and frequently a geometrical deformation can be observed through the thickness in the impact zone, due to permanent deformation of the damaged material. Thus, besides the stiffness reductions due to impact damage, the geometrical imperfection introduced by the impact is a factor that has to be taken into account. It is well known that buckling and postbuckling of thin-walled shell structures are sensitive to initial imperfections and therefore impact damage can be expected to change the postbuckling behaviour of composites considerably.

The behaviour of composites has received considerable attention in recent years [2]. The compressive behaviour of composites is of particular interest since the largest strength reductions usually are observed in compression [1]. These reductions are normally associated with delamination buckling and buckling induced delamination growth, and this has been the subject of extensive research for decades [3-6]. The studies have covered, e.g., one- and two-dimensional studies of delamination buckling to simulation of delamination growth due to delamination buckling [7-11].

The focus of the present work is to investigate how the presence of initial geometrical imperfections affects the structural response of delaminated composite panels during compressive loading. The effect of initial imperfections is one of the research topics on buckling behaviour of composite panels [12,13] that has gained attention lately. In the present study, the numerical simulations are made using an in-house finite element program, DEBUGS [14], which is developed to simulate delamination buckling and growth of single delaminations. However, no growth simulations are carried out in this study, the calculations are interrupted when the strain energy release rate at the delamination front reaches the critical strain energy release rate at which crack growth would start.

It is expected that the postbuckling effects due to geometrical imperfections are necessary to incorporate in a model for impact-damaged composites. However, an imperfection is not the only part required in a model of a damaged composite. A detailed description on micro-level of an impact damage is very difficult to achieve, consequently attempts to model the damaged area by introducing reduced material stiffness in that area, i.e. a soft-inclusion, have been carried out [15,16]. These attempts have shown promising results but have not really captured the responses seen in experiments on impact-damaged composites [17,18]. Combining soft inclusions and geometrical imperfections is a possible continuation of the modelling of impact damage since, as is seen in this report, imperfections may influence the postbuckling response considerably.

2. Computational method

The numerical calculations performed for studying the influence of initial geometrical imperfections on the structural response of composites are performed using DEBUGS. DEBUGS is a program system developed for simulation of buckling and buckling-induced interlaminar crack growth in composite panels. The commercial finite element program ADINA, provided by ADINA R&D, Inc., USA, is used as the primary solver in the structural analysis of the delaminated composite panels. Non-linear shell theory is used to model the composite plate. Fracture mechanics parameters are calculated within DEBUGS to examine when delamination growth will occur, here the energy strain release rate, *G*, is the most important parameter for this purpose. Moreover, a contact algorithm is employed to ensure that no inter-penetration of the opposite delamination surfaces will appear.

No description of DEBUGS is incorporated in this paper. For a complete description of the theoretical model and its finite element implementation, the papers [9,10,19] and the references therein should be consulted.

3. Numerical examples

In order to investigate the influence of initial imperfections on the structural response during compressive loading, several numerical computations are evaluated. Different parameters are varied during these tests. The main purpose is to explore how different shapes and sizes of the imperfections affect the postbuckling response

3.1 Test specimens

Two different plate geometries are considered. The delamination is in both cases circular with a diameter of 60 mm. For the first geometry, a plate, 150x150 mm, with a 32 layers quasi-isotropic lay-up, $[(0/45/-45/90)_s/(90/-45/45/0)_s]_2$, is chosen. This geometry was studied experimentally in [18]. The 0°-direction is parallel to the x_1-direction, i.e. in the same direction as the applied load (see Fig. 1). For the other plate geometry, the same lay-up is used, but the plate is 230x150 mm in that case. The material properties of the HTA/6376C carbon fibre/epoxy material used in the analyses are:

E_{11}=131 GPa, $E_{22}=E_{33}$=10.4 GPa, $G_{12}=G_{13}$=5.2 GPa,
G_{23}=3.9 GPa, $\nu_{12}=\nu_{13}$=0.3, ν_{23}=0.5, Ply thickness=0.13mm.

This material has been thoroughly investigated earlier. The delaminations are situated at the 5th ply interface for both of the plate geometries.

3.2 Geometrical imperfections

The numerical calculations are executed using different types of imperfections. In common for all the introduced imperfections, in this paper, is that they in different ways are based on the buckling mode shapes evaluated by linear buckling analysis, either local or global buckling mode shapes. The imperfections are introduced by modifying the geometry of the plate, right before the start of the postbuckling procedure in the DEBUGS package. The effects of the various shapes of the geometrical imperfections are seen in the next paragraphs.

3.3 Numerical examples

3.3.1 Square plate

The square 150x150 mm plate with a circular delamination of radius 60 mm is considered in the examples presented in this subsection. The loaded edges are clamped and the unloaded are free in these examples.

For this geometry a FE-mesh, which uses ‘double symmetry’, is used, see Fig. 1. This is an option, which the DEBUGS tool provides and is used here to save computational time, even though the geometry is not completely symmetric. The lay-up of the laminate is quasi-isotropic, however, the sublaminates are unbalanced and consequently introduce a slight asymmetry to the problem. Thus, a small error is introduced, but since the same error appears in all the calculations qualitative comparisons are still relevant.

The delamination is located at the 5th ply interface in these simulations. This implies that the thickness of the upper sublaminate is 0.80 mm (5x0.13mm). The imperfection sizes are determined from this value as DEBUGS has a built-in function to define the imperfection size in relation to the delamination thickness. Thus, an imperfection size of, e.g., 10% indicates, in this case, that the largest discrepancy from the non-deformed shape is 0.08 mm.

In Fig. 2, load-deflection relations for various imperfection sizes are shown. The numerical calculations are interrupted when the maximum strain energy release rate at some point along the delamination front, G_{max}, reaches the critical strain energy release rate, G_c=450 J/m^2, i.e. when the delamination growth would start if the simulation would have continued. No delamination growth is simulated in this study. However, in some of the curves presented later on, especially for the larger imperfections, the calculations were interrupted before the critical strain energy release rate, G_c, was reached, after a pre-selected maximum number of iterations. The point where the deflections are registered is located at the centre of the delamination, as it will be in all the other

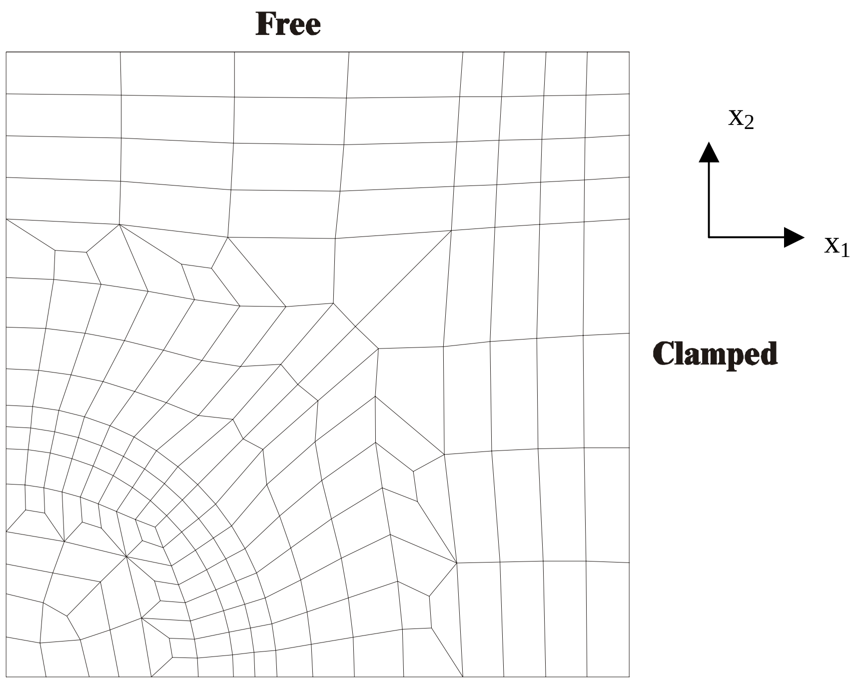

Fig. 1 The mesh for the square plate, using the ‘double symmetry’ option.

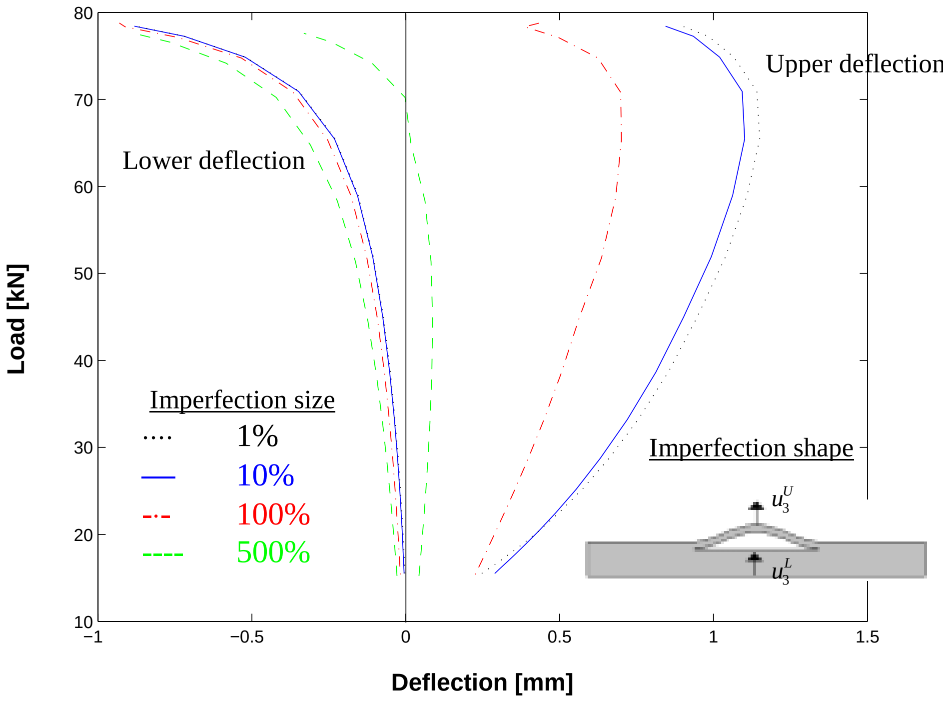

Fig. 2 Load-deflection curves at the centre of the panel obtained with varying sizes of the local buckling mode imperfection.

load-deflection plots. The imperfection has the same shape as the lowest local buckling mode shape, i.e. the thin upper sublaminate is distorted while the shape of the thicker sublaminate below the delaminations is more or less unchanged. A draft of the shape of this imperfection is also shown in Fig. 2. The presented deflections are deviations from the initial imperfect shape, thus the true deviation from the perfect plane shape is given by adding the initial imperfection size to the deflection values shown in the figure. It is seen from the figure that deflections from the initial shape varies considerably. The general trend of the deformation is, however, kept during the loading of the compressive force for this imperfection shape, i.e. the upper and lower surfaces move at the end of the loading in the same direction, and the delamination starts to close.

The imperfection, which is imposed on the panel in the simulations shown in Fig. 3, is created by applying the same deformed shape, defined by the form of the upper sublaminate of the local buckling mode shape, to both the upper and lower sublaminate, see sketch in Fig. 3. For the two smallest imperfections, no difference in the responses can be seen here compared to the previous imperfection type shown in Fig. 2. However, when this imperfection type gets larger, approximately when the imperfection is as large as the thickness of the upper sublaminate, a completely different response pattern is observed. Then, the thick lower sublaminate, under the delamination, also starts to buckle in the same direction as the initial imperfection. As a result of this, the overall motion of the panel is in this direction, since it is the thicker sublaminate which governs how the thinner sublaminate eventually moves due to the restoring forces, which appear on the thinner laminate. While the parts on the different sides of the delamination still separates for the second largest imperfection, the parts almost move as a unit for the largest imperfection.

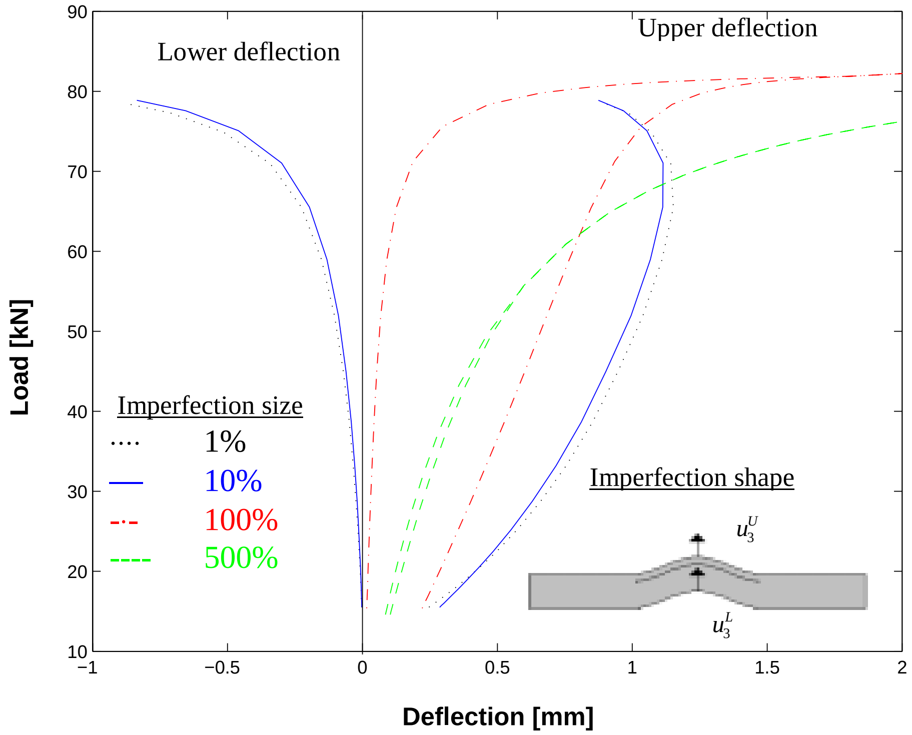

Fig. 3 Load-deflection curves at the centre of the panel obtained with varying sizes of the modified local buckling mode imperfection (the lower and the upper sublaminates have the same shape).

In the next example, shown in Fig. 4, the local buckling mode shape of the upper sublaminate is once again used to create the initial imperfection. The difference between this example and the previous one (shown in Fig. 3) is that the imperfection introduced at the lower sublaminate only is 50% of the imperfection of the thin upper sublaminate. Thus, the imperfection size values, stated in the figure, only apply for the upper sublaminate. For this imperfection type, only the largest imperfection shows the behaviour where both the upper and lower laminates moving in the same direction as the imperfection. From these curves, it seems like that the surfaces penetrate into each other, however, this is not the case since, as pointed out earlier, the curves show the deflections from the initial shape. At the beginning of the simulation, there is a gap between the surfaces and at the end when the gap is closed; the deflection curve looks like in Fig 4 for the largest imperfection. For the other sizes of the imperfections, the same type of deflection behaviour is observed.

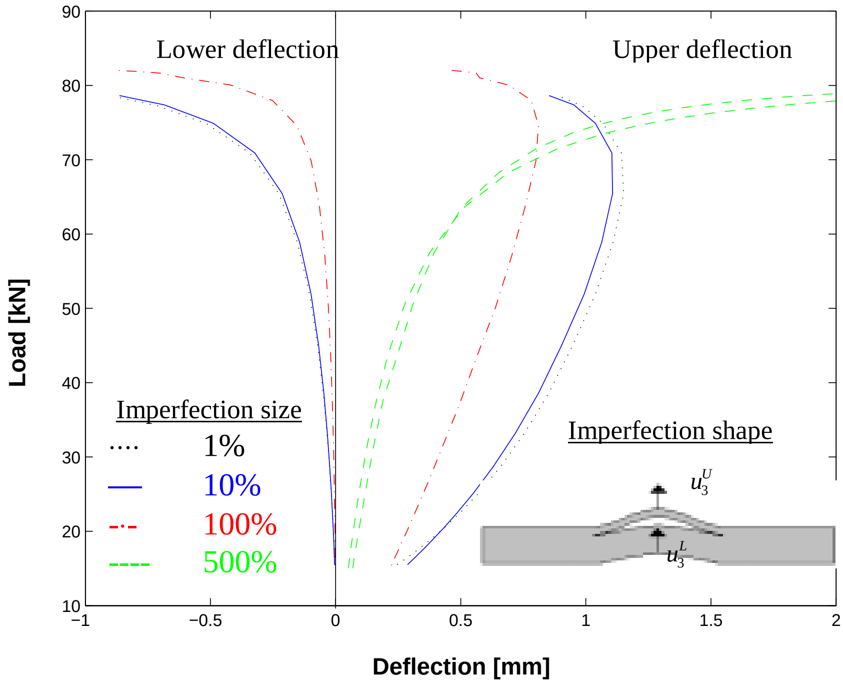

Fig. 4 Load-deflection curves at the centre of the panel obtained with varying sizes of the modified local buckling mode imperfection (lower sublaminate imperfection size, 50% of the imperfection of the upper sublaminate).

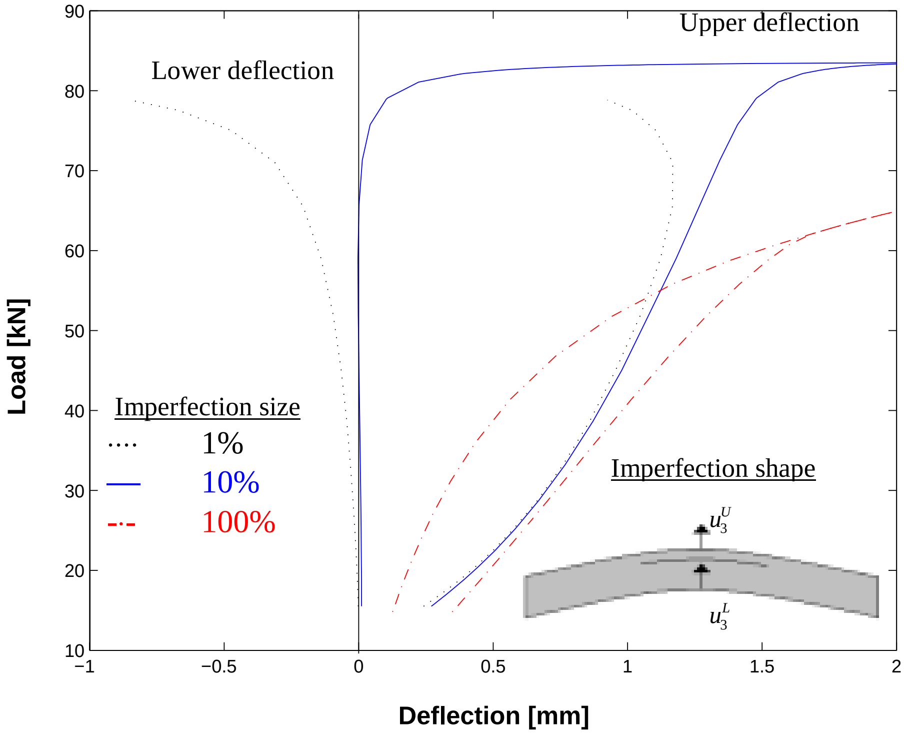

Fig. 5 Load-deflection curves at the centre of the panel, obtained with varying sizes of the lowest order global buckling mode shape.

The last type of imperfection that is investigated is, when the initial shape has the same form as the lowest order global buckling mode, which has the shape indicated in Fig. 5. The load-deflection behaviour of the midpoint, for varying sizes of the global mode shape imperfection can be seen in Fig. 5. It is seen that the change in postbuckling behaviour occurs at a lower level of the imperfection size compared to the other imperfection shapes.

3.3.2 Rectangular plate

The second geometry that is studied is a 230x150 mm panel, where the load is applied along the shorter side, which is clamped, while the longer side is simply supported. This geometry is of interest because it has been investigated earlier at FOI/FFA [18]. The assumed geometry of the delamination is the same as for the quadratic plate, i.e. with a diameter of 60 mm.

The first and second global buckling loads are about the same magnitude for this geometry. Thus, it is possible that either of these modes can be excited during the loading process. As a consequence of that, the model of this plate does not use the 'double symmetry' option, provided by DEBUGS, that was used in the previous example, since the two lowest order buckling modes cannot be captured if this option is used. Thus, the 'no symmetry' option in DEBUGS is used for the rectangular plate, see Fig. 6. However, no sign of mode jumping was seen during the loading processes, for the cases that were tested.

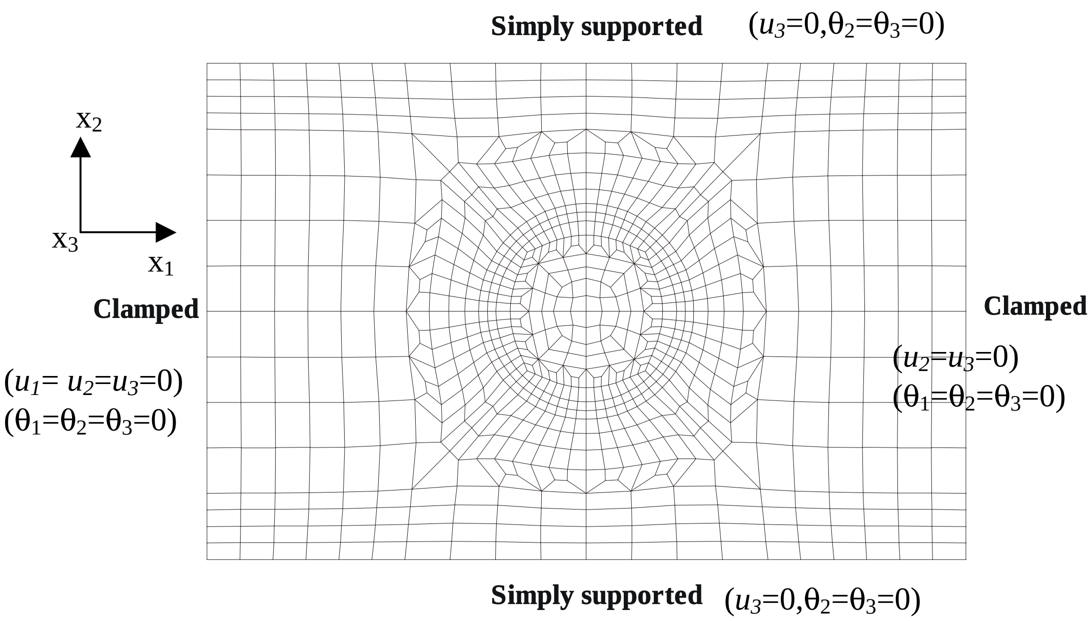

Fig. 6 The mesh for the rectangular plate, using the 'no symmetry' option.

The same variations of the initial imperfections in shape and size are used here as for the quadratic plate. The results of how the deflection of the centre point of the plate, above and beneath the delamination, varies during the loading of the plate are shown in Figures 7-9. The results for this geometry with the rectangular plate show the same kind of trends as for the rectangular plate. Consequently, the same conclusions apply to the results here, as in the previous case.

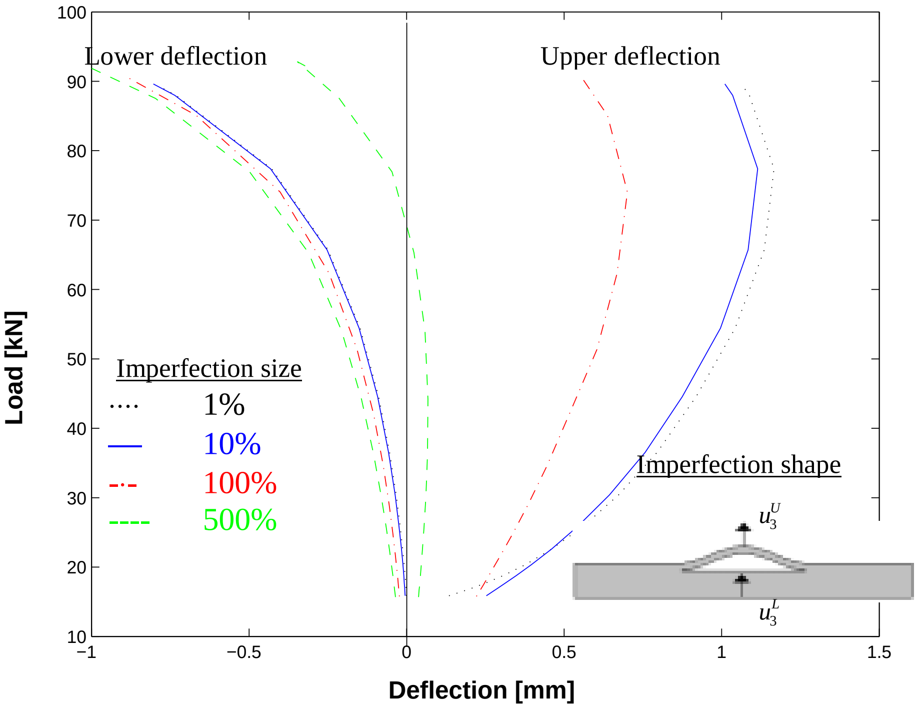

Fig. 7 Load-deflection curves at the centre of the panel for the rectangular plate, obtained with varying sizes of the local buckling mode imperfection.

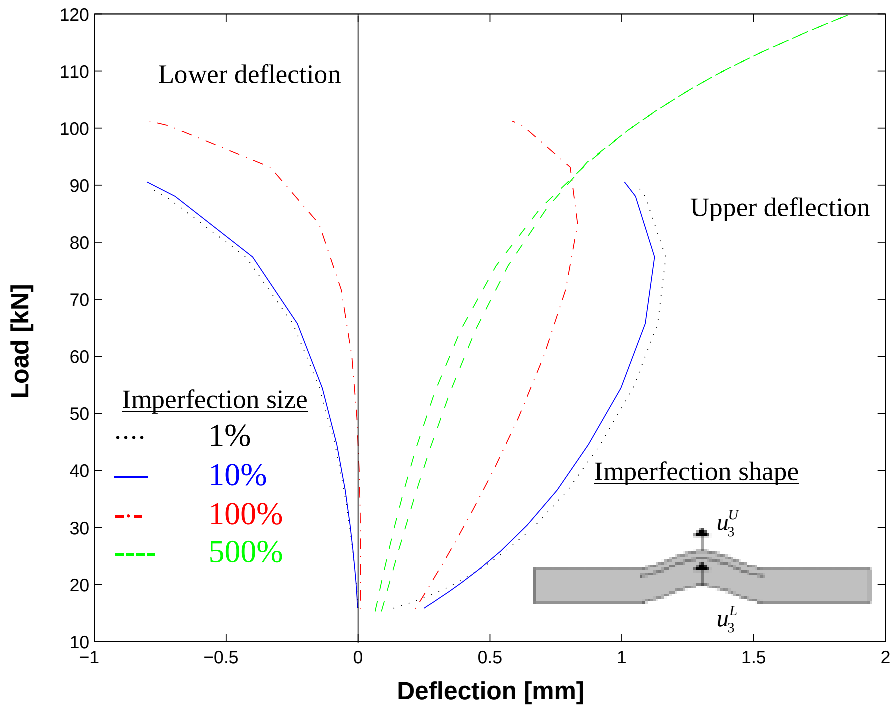

Fig. 8 Load-deflection curves at the centre of the panel for the rectangular plate, obtained with varying sizes of the modified local buckling mode imperfection (the lower and the upper sublaminates has the same shape).

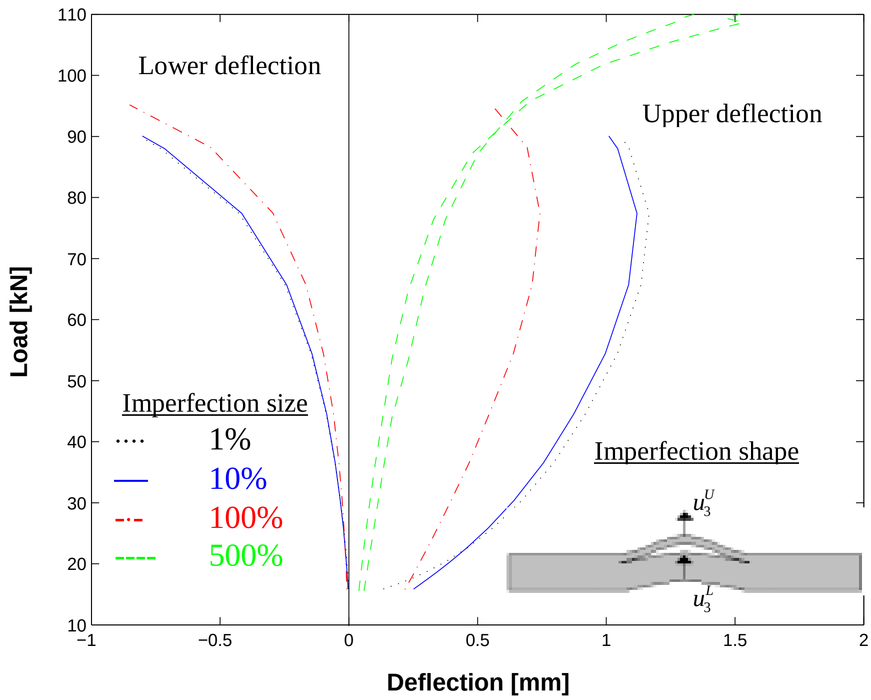

Fig. 9 Load-deflection curves at the centre of the panel for the rectangular plate, obtained with varying sizes of the modified local buckling mode imperfection (lower sublaminate imperfection size, 50% of the imperfection of the upper sublaminate).

4. Conclusions

In this report, the effect of geometrical initial imperfections on postbuckling behaviour of composite laminates with delaminations is studied numerically. For this purpose the ADINA-based program system DEBUGS is used, which is well suited for investigations of this kind. The imperfections are included as a modified geometry of the composite at the beginning of the loading process. The shapes of the imperfections, in this study, are all different variations of the global and local buckling mode shapes, which can be obtained through DEBUGS by linear buckling analysis. Other geometrical imperfections can be included in DEBUGS for similar analyses with a minor effort. Thus, analyses of this type are not restricted to the imperfections, based on the buckling mode shapes that are studied here.

The numerical tests and parameter studies made in this report show that initial imperfections may have an influence on the postbuckling response and consequently also on the buckling-driven delamination growth, which affects the residual strength of composites. In general, initial imperfections tend to reduce the opening mode during buckling of the two sublaminates. Sufficient local imperfections may cause a reversed global buckling direction. The initial imperfections cannot alone describe, e.g., the initiation of delamination growth, but it seems that this factor cannot be neglected. Consequently, in a model of an impact damaged composite laminate, where the damaged zone, e.g., is described through a soft-inclusion with reduced stiffness, the initial imperfections also need to be included to allow a good representation of the damaged composite.

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References

1. Abrate, S. (1991), Impact on laminated composite materials, *Appl. Mech. Rev*., 44:155-190.

2. Dvorak, G.J. (2000), Composite materials: Inelastic behavior, damage, fatigue and fracture, *Int. J. Solids Struct.*, 37:155-170.

3. Krishna Murty, A.V. and Reddy, J.N. (1993), Compressive failure of laminates and delamination buckling: a review, *Shock Vibr*. *Digest*, 25:3-12.

4. Bolotin, V.V. (1996), Delaminations in composite structures: its origin, buckling, growth and stability, *Composites Part* B, 27B:129-145.

5. Hutchinson, J.W. and Suo, Z. (1992), Mixed mode cracking in layered materials, *Advances Appl. Mech.*, 29:63-191.

6. Moradi, S. and Taheri, F. (1999), Postbuckling analysis of delaminated composite beams by differential quadrature method, *Composite Structures*, 46:33-39.

7. Chai, H., Babcock, C.D. and Knauss, W.G. (1981), One-dimensional modelling of failure in laminated plates by delamination buckling, *Int. J. Solids Struct.*,17:1069-1083.

8. Chai, H. and Babcock, C.D. (1985), Two-dimensional modelling of failure in delaminated laminates, *J. Compos. Mater.*, 19:67-98.

9. Nilsson, K.-F., Thesken, J.C., Sindelar, P. and Giannokopoulos, A.E. and Storåkers, B. (1993), A theoretical and experimental investigation of buckling induced delamination growth, *J. Mech. Phys. Solids*, 41:749-782.

10. Nilsson, K.-F., Asp, L.E., Alpman, J. and Nystedt, L. (2001), Delamination buckling and growth for delamination at different depths in a slender composite panel, *Int. J. Solids Struct*., 38:3039-3071.

11. Nilsson, K.-F., Asp. L.E. and Sjögren A. (2001), On transition of delamination growth behaviour for compression loaded composite panels, *Int. J. Solids Struct.*, 38:8407-8440.

12. Romeo, G. and Frulla, G. (1997), Post-buckling behaviour of graphite/epoxy stiffened panels with initial imperfections subjected to eccentric biaxial compression loading, *Int. J. Non-linear* Mechanics, 32:1017-1033.

13. Kim, K. and Voyiadjis, G.Z. (1999), Non-linear finite element analysis of composite panels, *Composites: Part B,* 30:365-381.

14. Zeng, L. (2001), User's Manual for DEBUGS 2.0 – A finite element program for delamination buckling and growth simulation of laminate composite panels, Technical Report, FOI-R--0239--SE, Swedish Defence Research Agency, Sweden.

15. Zeng, L. and Olsson R. (2002), Buckling-induced delamination analysis of composite laminates with soft-inclusion, Technical Report, FOI-R--0412--SE, Swedish Defence Research Agency, Sweden.

16. Nyman, T., Bredberg, A. and Schön, J. (2000), Equivalent damage and residual strength for impact damaged composite structures, *J. Reinforced Plastics Comp.*, 19:428-448.

17. Asp, L., Nilsson, S. and Singh, S. (1998), An experimental investigation of the Influence of delamination growth on the residual strength of impacted laminates, FFA TN 1998-52, The Aeronautical Research Institute of Sweden, Bromma.

18. Nilsson, S. (2000), Tests and analytical prediction of compressive strength of impacted composite laminates, FFA TN 2000-16, The Aeronautical Research Institute of Sweden, Bromma.

19. Nilsson, K.-F. and Giannakopoulos, A. (1995), A finite element analysis of configurational stability and finite growth of buckling driven delamination, *J. Mech. Phys. Solids*, 43:1983-2021.