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Technical Notes

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Finite Strip Buckling Analysis of Some Composite Stiffened Box Sections

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Introduction

THIN-WALLED structures have become very popular in structural engineering because of their high strength-to-weight ratio. These structures can be precisely analyzed using the finite element method. However, for a certain group of problems, such as prismatic plate assemblies, the usual finite element analysis might be extravagant. Among many attempts to find an efficient analysis of such class of problems, the finite strip method is considered to be appealing. The finite strip method (FSM) can be considered as a kind of finite element method in which a special element called strip is used. The basic philosophy is to discretize the structures into longitudinal strips and interpolate the behavior in the longitudinal direction by different functions, depending on different versions of FSM and in the transverse direction by polynomial functions. A great deal of research has been carried out in this area to investigate the applicability of method. Subsequently, many useful extensions have been developed.

Cheung,[1] among others, can be considered as the pioneer who first presented the concept of finite strip method. Subsequently, other researchers developed different variations of the method and applied them to different problems. To name a few, Graves-Smith and Sridharan[2] proposed the first FSM formulations for isotropic plate structures under edge loading. Loughlan[3] used a FSM approach to study the buckling of composite-blade-stiffened square box sections under pure compression and bending. The results presented by Loughlan are only for stiffened boxes with cross-ply layup configuration for both box and stiffeners. He studied the effects of varying the stiffener ratio on the buckling load capacity of the section.

More recently, the authors of the current Note generated a FORTRAN code on the basis of semi-analytical FSM approach in which the representation of longitudinal displacement fields are by trigonometric functions and in the transverse direction by polynomial functions.

Space limitations preclude the presentation of the development of the aforementioned finite strip approach in this Note, but the detailed formulation of this FSM theory can be found in some recent works[4,5] of the authors. In these works the related code has been validated by comparing the obtained results with those already available in open literature for composite stiffened panels subjected to in-plane compression and shear loading. The authors then carried out a set of parametric studies to investigate the buckling properties of a composite Z-section beam under compression.

In this Note, the developed finite strip approach is implemented to investigate the buckling behavior of some composite stiffened boxes, which are loaded under pure compression. The effects of different layup configuration of stiffeners (i.e., unidirectional, cross-ply, and angle-ply) and the effects of stiffener shapes (i.e., blade stiffener and L-type stiffener) on the buckling load capacity of the stiffened boxes are studied.

These structures can schematically represent the wing box of an aircraft or a part of a helicopter blade.

Results and Discussion

The structural configuration considered is that of stiffened box sections manufactured from high-strength carbon-epoxy preimpregnated ply sheets. The material properties of a single ply are as follows: $E_1 = 140$ GPa, $E_2 = 10$ GPa, $G_{12} = 5$ GPa, $\upsilon_{12} = 0.3$, and $t = 0.125$ mm.

To achieve a fairly comprehensive parametric study, some dominating design parameters such as the layup configuration in stiffeners (i.e., unidirectional, cross-ply, and angle-ply) and the stiffener shape (i.e., the L-shape and the blade stiffeners) are considered in this Note. The dimensions of the aforementioned stiffened box sections are depicted in Fig. 1a.

The nondimensional compressional buckling parameter K_c is the ratio of σ_s to σ_{box}. It is noted that σ_s is the critical compressive buckling stress of the structure, and σ_{box} is the critical compressive buckling stress of a nonstiffened square box section with the dimensions and layup sequence as those of the skin of the corresponding stiffened box.

To ensure that the modeling is achieved with a sufficient number of strips, a convergence study has been carried out. In this study, two finite strip models with totally different number of strips are constructed for each stiffened box section. Because of the symmetry of the sections, only half of the section is modeled. The blade-stiffened section is modeled initially by 68 strips and then by 136 strips. Considering the fact that the current finite strip formulation is based on the minimization of the potential energy, an upper bound estimate of the structure stiffness is expected to achieve for a converged solution. Hence, the increase in the number of strips should result in lower values of buckling coefficient. This behaviour has clearly been noticed for the aforementioned finite strip models considered for the blade-stiffened box section. However, the difference between the nondimensional buckling parameters obtained by the application of the just-mentioned models has been insignificant (i.e., less than 0.11%). This has led to the conclusion that 68 strips are sufficient to obtain a converged solution for the blade-stiffened section. The same study has been carried out for the L-type stiffened box section implementing two models: one with 76 strips and the other with 152 strips. This has indicated that a converged solution can be achieved with 76 strips. In the remainder of this Note, as a result of the convergence study the blade and L-shape stiffened box sections are modeled using 68 and 76, respectively. The corresponding finite strip models are depicted in Fig. 1b.

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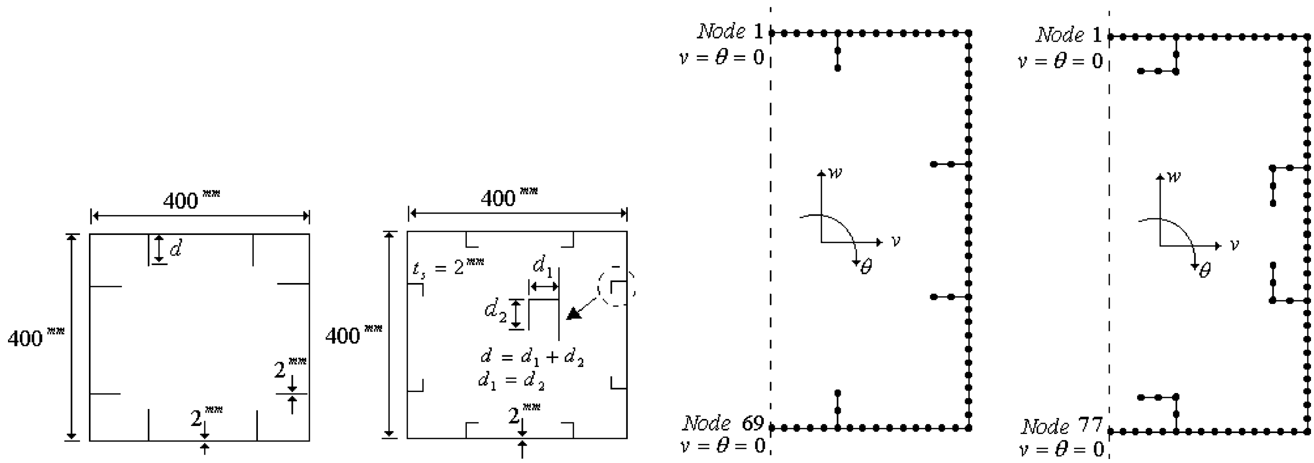
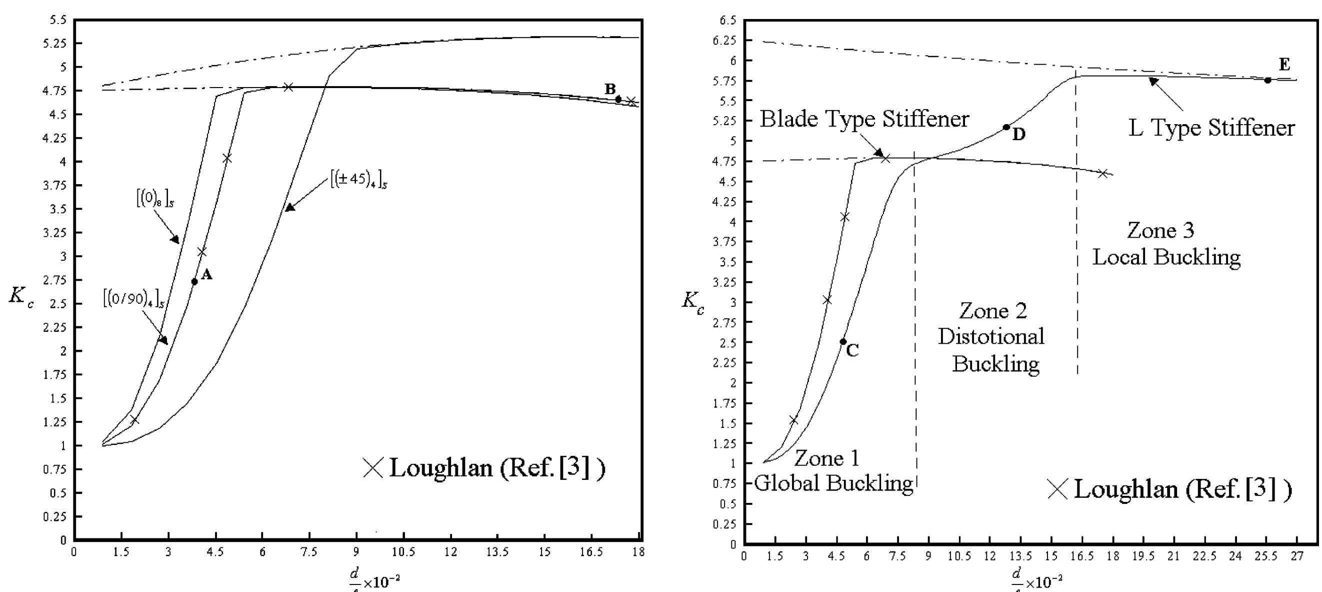


a) b)

Fig. 1 Dimensions and finite strip models of the stiffened box sections.



a) b)

Fig. 2 Buckling properties of stiffened box sections.

Having established the appropriate FSM models, the effects of the aforementioned design parameters (i.e., the layup configurations in the stiffeners and the stiffener shapes) on the buckling load capacity of the structure are considered next.

Layup Configuration of Stiffeners

The blade-stiffened box section is chosen to study the effects of lay up configuration of the stiffeners. Although there are a large number of possible combinations of fiber orientations and ply stacking sequence in layered composite material construction, space limitations preclude the presentation of a wide spectrum of results in this Note. Thus, selected configurations have been chosen for analysis, and these are shown to portray both interesting and informative buckling features.

Although the layup configuration for the box skin is assumed to be symmetric cross-ply, three different layup configurations, that is, unidirectional, symmetric cross-ply, and symmetric angle-ply are used for the stiffeners. The total number of layers in both the skin and the stiffeners is 16. Thus, the skin and the stiffeners are of the same thickness, which is 2 mm.

The compressive buckling load capacity of the structure is plotted as a function of stiffener width in Fig. 2a. The effects of fiber orientation in the stiffeners are also highlighted in the figure. The good agreement between the current results and those of Ref. 3 demonstrates the validity of the obtained results.

For comparative purposes, the local buckling paths of the composite boxes are plotted in the figure by the dashed curves as opposed to the solid curves, which represent the general behavior of the section. To plot the dashed curves, it is assumed that all of the junctions between component plates of the section are constrained against movement in any directions. The solid curves show that by increasing the stiffener width the compressional buckling load capacity of the section increases, and at a specific stiffener width the maximum buckling load capacity of the structure is attained. The examination of the mode shapes reveals that at low stiffener width the mode of buckling is global in nature. (See Fig. 3, which represents the buckling mode shape of the blade stiffened section at the crest

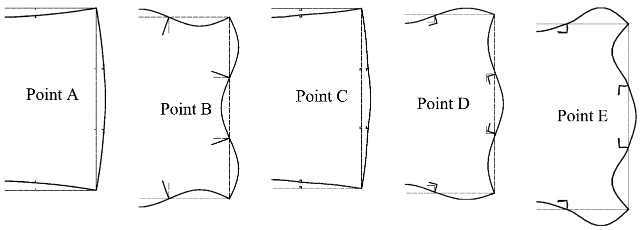


Fig. 3 Buckling mode shape of the stiffened box sections at the crest of buckle.

of buckle for point A in Fig. 2a.) In this region, the buckling is more dominant in the skin, which is somewhat restrained against buckling by the stiffeners. By increasing the stiffener width and passing the maximum point, the solid and dashed curves tend to merge. This means that the buckling behavior of the section has shifted toward being more local. (See Fig. 3, which represents the buckling mode shape of the blade-stiffened section at the crest of buckle for point B in Fig. 2a.)

The effects of stiffener fiber orientation on the compressive buckling capacity of the stiffened box sections are examined. It can easily be seen in Fig. 2a that when the dominant buckling mode of the section is global the unidirectional flanges produce the best compressive buckling performance of the section. This is because when the mode of buckling is global the stiffeners experience the in-plane bending. Thus, the stiffeners that have the greatest longitudinal membrane stiffness are able to resist more effectively the in-plane bending of the overall buckling modes. This means that when the buckling mode is global the unidirectional layup sequence is the optimum fiber orientation for flanges, and the angle-ply layup configuration is the worst. However, when the dominant buckling mode of the section is local the behavior changes. In this case, it can be seen in the figure that the stiffeners with the angle-ply fiber orientation produce the maximum compressive buckling capacity of the structure.

This can be explained by the fact that when the buckling mode is local the junctions of the skin and stiffeners remain straight, and the skin of the flanges and the webs experience out-of-plane bending and twisting. In this case, the junctions can be considered to act as torsional springs that impose torsional stiffnesses on both of the flange skin as well as the web skin. Thus, by increasing the torsional stiffness of these so-called springs the local-compressive buckling capacity of the section is expected to be enhanced. Obviously, this purpose is served by the use of angle-ply, which has the highest transverse bending and twisting stiffness among other layup configurations under investigation, for the stiffeners.

Different Stiffener Shapes

In this part, the effects of two types of stiffener shapes (i.e., L-type stiffener and blade stiffener) on the buckling load capacity of the structure are examined. The layup configuration in both of the skin and the stiffeners is a symmetric cross-ply configuration. The variation of compressive and bending buckling load capacity with variation in stiffener width is shown in Fig. 2b.

It is emphasized that for the L stiffener, d corresponds to the summation of the flange and web width of the stiffener. Moreover, the width of flange and web of the L-type stiffener is assumed to be equal. It is obvious that for a given value of d/l ratio, the structural weight is the same for both blade and L-type stiffened box sections. The dashed lines on the figure represent the local buckling path of the structure. The buckling mode shapes of the sections for some selected points in Fig. 2b (i.e., points C, D, and E) are depicted in Fig. 3.

It can be seen that for the smaller stiffener sizes the mode of buckling is global in nature, and by increasing the stiffener size the mode of buckling shifts toward being local. Obviously, this behavior is quite the same as that seen earlier with respect to the results given in Fig. 2a.

It can be seen in Fig. 2b that the curve corresponding to L-type stiffener experiences three changes in its curvature, hence producing three zones. In the first zone, the mode of buckling is global (see Fig. 3, point C), whereas in the second zone the mode of buckling is distortional in which the junctions between L-type stiffener and the skin remain straight but the junctions of webs and flanges are moved (see Fig. 3, point D).

In the third zone, the buckling mode is local in nature, and all of the junctions are remain straight (see Fig. 3, point E).

Figure 2b shows that when the mode of buckling is global in nature the blade-stiffened sections present a higher buckling load capacity than that presented by L-type stiffened sections. This can be explained by the fact that when the mode of the buckling is global the stiffeners experience in-plane bending; thus, a stiffener with a higher level of membrane stiffness (i.e. blade stiffener) will resist the in-plane bending more effectively.

It is also seen that the maximum buckling load capacity of the L-type stiffened box is higher than the maximum buckling load capacity of a blade-stiffened box. This implies that when the mode of buckling is local in nature the L-type stiffeners show a better performance. As mentioned earlier, when the mode of buckling is local the attachment line between skin and the stiffener will act as a torsional spring. Thus, the L-type stiffeners are capable of imposing a higher degree of torsional stiffness at this line than that afforded by blade stiffeners.

Conclusions

A finite strip approach has been implemented to predict the buckling behavior of composite stiffened boxes beams subjected to pure compression. The effects of two important design parameters (i.e., the stiffener layup configuration and the shape of the stiffeners) are considered in this Note.

The study of the results revealed the fact that the optimum fiber orientation for stiffeners and the optimum stiffener shape have great dependency on the buckling mode of the section. When the buckling mode is global, the unidirectional stiffeners and the blade stiffeners seem to be more appropriate. Conversely, when the mode is local, angle-ply layup configuration and the L-type stiffeners proved to be a more suitable choice.

Finally, it is worth mentioning that the use of the developed finite strip method code allows designers to specify the optimum stiffener size for a given layup configuration.

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