Overall Buckling and Wrinkling of Debonded Sandwich Beams: Finite Element and Experimental Results

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Abstract. Overall buckling and wrinkling of debonded sandwich beams under compressive loads were analyzed by both finite element and experimental methods. In the finite element method, a quarter and a half models of the specimens were analyzed. It shows that a quarter model is not adequate to analyze buckling of debonded sandwich beams, since it will disregard overall buckling mode that may occur in sandwich beams having compressive loads. At least a half model should be used to analyze buckling of sandwich beams. A finite element program UNA was used extensively to analyze the buckling loads. Experimental buckling of sandwich beams was carried out using a compression testing machine. Two LVDTs were used to measure deflections of the specimen during experimental loading. The loads were measured using load cells available in the machine. Specimens having core thickness of 45 and 75 mm were tested to represent overall and wrinkling modes respectively. The delamination lengths were 20, 60 and 80 mm, which represent 10, 30 and 40% of the beam length. The results show that the differences between experimental and finite element methods were less than 10%. Both overall buckling and wrinkling modes were shown in these specimens.

Keywords: *debonded sandwich beams; overall buckling; wrinkling; finite element method.*

1 Introduction

Overall buckling and wrinkling are two instability phenomena of sandwich structures under compressive or shear load. Generally, when the core is thin, sandwich structures will exhibit overall buckling mode due to compressive or shear loads, where the deformation modes are across the length of the structures. When the core is thick, however, the sandwich structures may exhibit wrinkle due to compressive and shear loads. There are two types of wrinkle: symmetric (hour glass mode) and asymmetric (snake mode) wrinkles. Figure 1 shows typical overall buckling and wrinkling of sandwich beams due to compressive loads.

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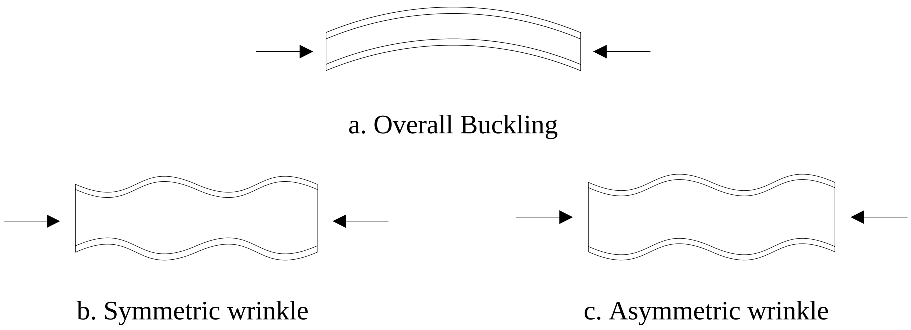


Figure 1 Instabilities of sandwich beams due to compressive loads [4].

Several researches had studied these phenomena. Allen [1] developed equations to predict the critical loads for both overall and wrinkle modes. He assumed a plate on elastic foundation to calculate the wrinkling loads. The stiffness of the core was modeled as springs which connected the face and the middle plane of the core. Therefore, by doing so, he assumed a symmetric wrinkle. Benson and Mayers [2] developed a general methodology that can calculate both the overall buckling and wrinkling loads of sandwich panels having isotropic faces. Webber [3] using different approach was able to calculate overall buckling and wrinkling of both sandwich panels and beams having orthotropic faces. Hadi and Matthews [4] developed further to include anisotropic faces. However, the researches above assumed a perfect sandwich structure; *i.e.* where the core is fully bonded with both faces. Therefore, no debonded area occurs between the core and the faces.

In practice, however, debonded region between the core and the faces cannot be prevented. This could be the results of imperfection during manufacturing processes or due to impact damage. Since the stiffness of sandwich structure is mostly due to the perfect bond between the core and the faces, this imperfection may result to the decrease of its structural stiffness and may lead to catastrophic failure. Therefore, a complete understanding of the effect of debonding on the buckling and wrinkling of sandwich structures is necessary to insure a safer sandwich structure.

Sleight and Wang [5] used finite element method to predict buckling of debonded sandwich beams. Since the debonded region was symmetric, they only analyzed a quarter of the beams. By doing so, they restricted their analysis only for symmetric wrinkling mode. Frostig and Sokolinsky [6] studied buckling behavior of sandwich panels with a transversely flexible core that were debonded at one of their face sheet - core interface. Buckling response was studied numerically and the effects of length and location of the delamination, face sheet rigidities and boundary conditions on the critical loads and buckling modes were presented. Recently, Aviles and Carlsson [7] developed further Allen’s methodology into two dimensional cases (plates). Their numerical results were then compared with experimental data and it was shown that for large debonds the model tends to overpredict the buckling load.

In this paper, overall buckling and wrinkling of debonded sandwich beams will be analyzed using finite element method. The results will be then compared with experimental results.

2 Finite Element Analysis

In this analysis, a finite element code UNA [8] was used extensively. The pre- and post-processing used FEMAP. A 4-noded quadrilateral element was used to model both the faces and the core. Separate nodal points between face and core were created to model debonded region in the interface. Figure 2 shows schematic diagram of the problem.

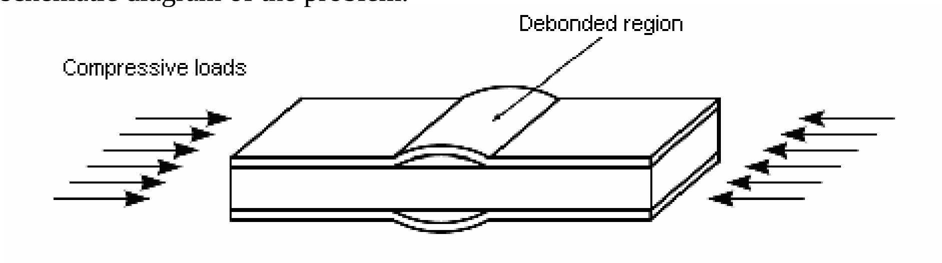
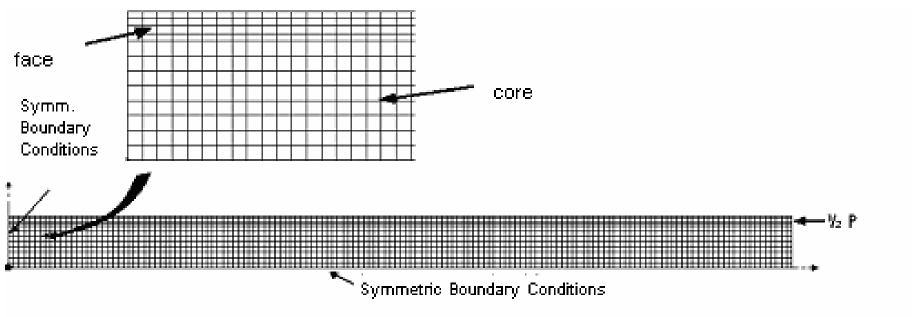
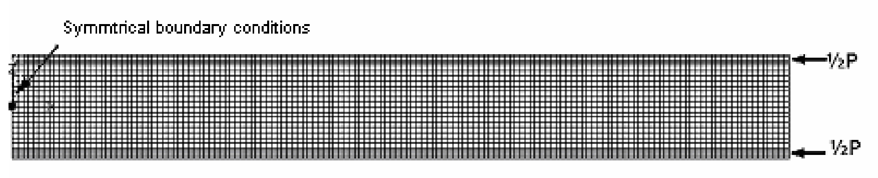


Figure 2 Schematic diagram of the problem.

Since the problem seems to be symmetric, Sleight and Wang [5] analyzed only a quarter of the beam. In this paper, we will analyze it using a quarter and also a half of the model and then compare the results. Figure 3 shows a quarter and a half finite element model of the beam.



(*a*) A quarter model as given in [5].



(*b*) A half model.

Figure 3 Finite element model of the debonded beam.

3 Experimental Method

The experiment used a compression testing machine available in the Department of Aeronautics and Astronautics ITB. The sandwich beam specimens were manufactured with CFRP $(+/-45^o/0^o)_s$ faces and polyurethane core. The bonding between the face and the core was produced using epoxy based adhesive liquid, except in the debonded area, where an aluminum film was placed between the faces and the core in order to produce the debonded region. The schematic diagram of the experimental method is given in Figure 4.

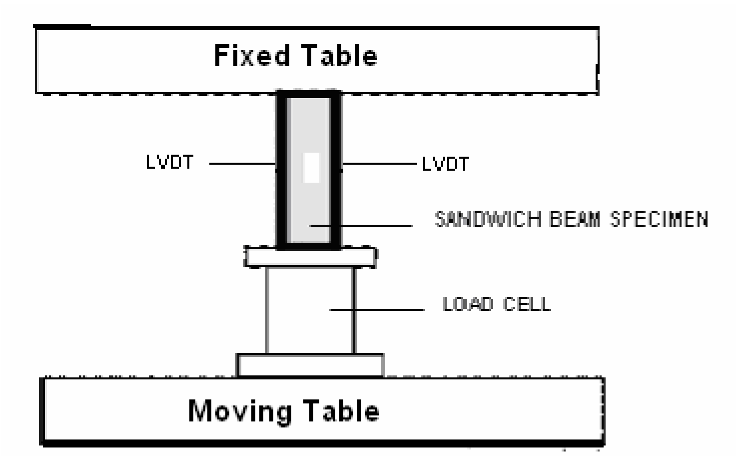


Figure 4 Schematic diagram of the experimental method.

Two *L*inear *V*ariable *D*isplacement *T*ransducers (LVDT) will measure transverse displacements at both sides of the specimens. While at the same time, the load cell will measure the loads. By combining those data we will able to produce load – displacement graphs during experiment and then the critical buckling load of the specimen could be calculated.

4 Results and Discussions

4.1 Comparison with the work of Sleight and Wang [5]

The material characteristics and beam geometry are as follows [5]:

Table 1 Material characteristic and beam geometry for Sleight and Wang [5]

Face	Aluminum E = 10.0 x 10^6 psi v = 0.3 thickness = 0.2 inch
Core	Isotropic E = 10000 psi v = 0.3 thickness = 1.6 inch
Dimension	Length = 30 inch

In the finite element analysis, 1,800 elements were used in the quarter model while in the half model, a double of those elements were used. The results are given in the Figures 5 and 6 for debonded length of 2 inch (6.67% of the total length.

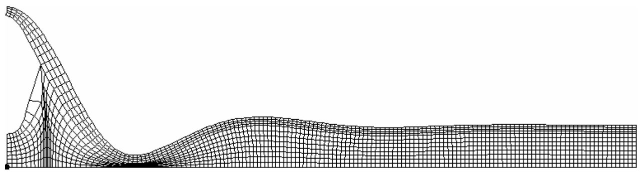
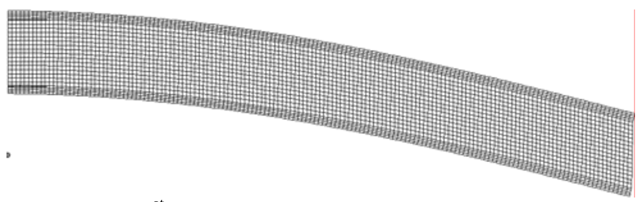


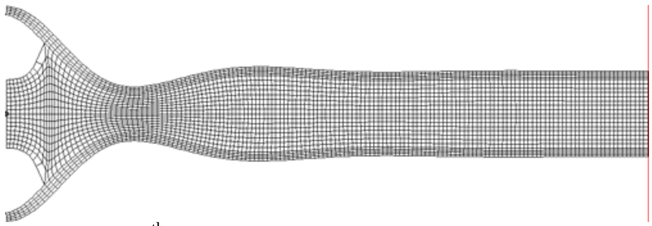
Figure 5 The 1st mode of debonded sandwich beam under compressive load using a quarter model (P_{crit} = 25,714 lb/in).

Similar result as Figure 5 was also found in Sleight and Wang [5]. Therefore, using a quarter model, we found that the critical buckling load (the lowest buckling load) was found to be 25,714 lb/in. The figure also shows that the local or wrinkle mode is dominant in this case.

Nevertheless, when we used a half model, dissimilar results were found. Figure 6 shows the results.



(a) The 1st mode of half model (P_{crit} = 6,527 lb/in)



(b) The 7th mode of half model (P_{crit} = 25,012 lb/in)

Figure 6 Buckling mode of debonded sandwich beam under compressive load using a half model.

When we compare Figure 5 and 6, we found that there is a similarity between the results of Figure 5 and 6.b, for both the buckling (wrinkling) mode and the critical buckling load. Nevertheless, using a quarter model as shown in Figure 5 over predict the buckling load, since it gives the lowest buckling load of 25,714 lb/in; where the actual buckling load of the beam was found to be 6,527 lb/in as was shown in Figure 6.a. Furthermore, the buckling mode was found to be in the overall buckling mode, not local or wrinkling mode as was found when a quarter models was used, as in Figure 5.

The finding above is important, since the quarter model over predicts the critical buckling load as many as four times the actual critical buckling load. Figure 7 shows the critical buckling loads of debonded sandwich beams. It shows that a quarter model over predict the buckling loads severely. For debonded area of over 40% of the beam length, however, the two models coincide.

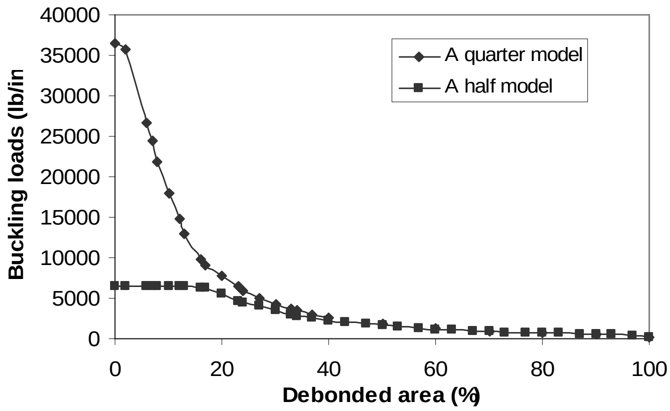


Figure 7 Buckling loads of debonded sandwich beams.

4.2 Comparison with experimental results

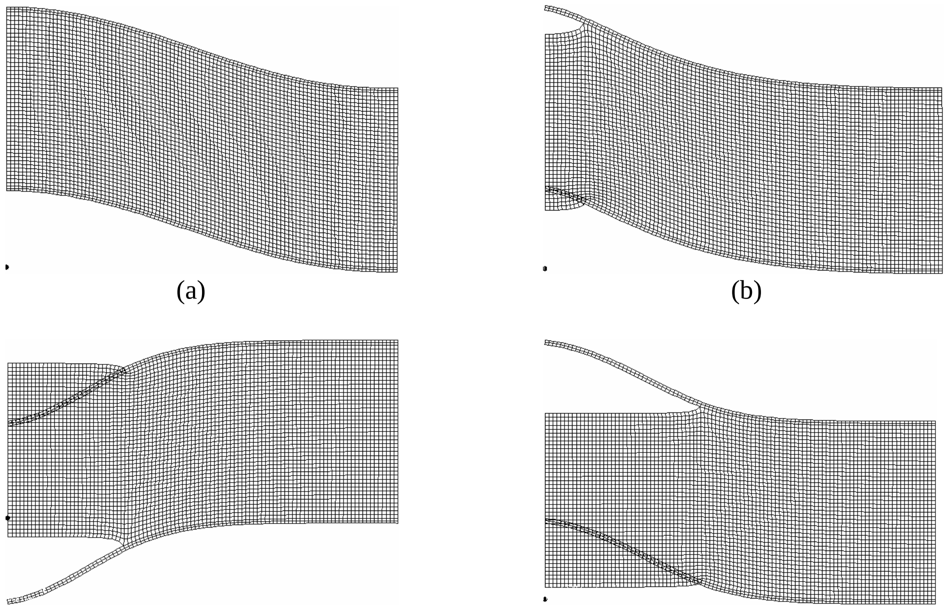
The material characteristics and beam geometry are given below:

Table 2 Material characteristic and beam geometry for experimental results.

Face	CFRP (+/-45°/0°)$_s$ E_1 = 148750 MPa ; E_2 = 3720MPa ; G_{12} = 1860 MPa v_{12}= 0.3 thickness = 1.2 mm
Core	Polyurethane E = 7896 MPa v = 0.3 thickness = 45 mm for overall buckling mode thickness = 75 mm for wrinkling mode
Dimension	Length = 200 mm

4.2.1 Overall Buckling Mode

The finite element result for overall buckling mode is given in Figure 8.



(a) (b) (c) (d)

Figure 8 Finite element buckling mode for 45 mm core thickness specimens. (a) without delamination, (b) 10% delamination, (c) 30% delamination, (d) 40% delamination.

Figure 8 shows that specimens having core thickness 45 mm fail in overall buckling mode. The separation of the face skin and the core (delamination) is clearly seen in this figure.

4.2.2 Wrinkling Mode

The finite element result for wrinkling mode is given in Figure 9.

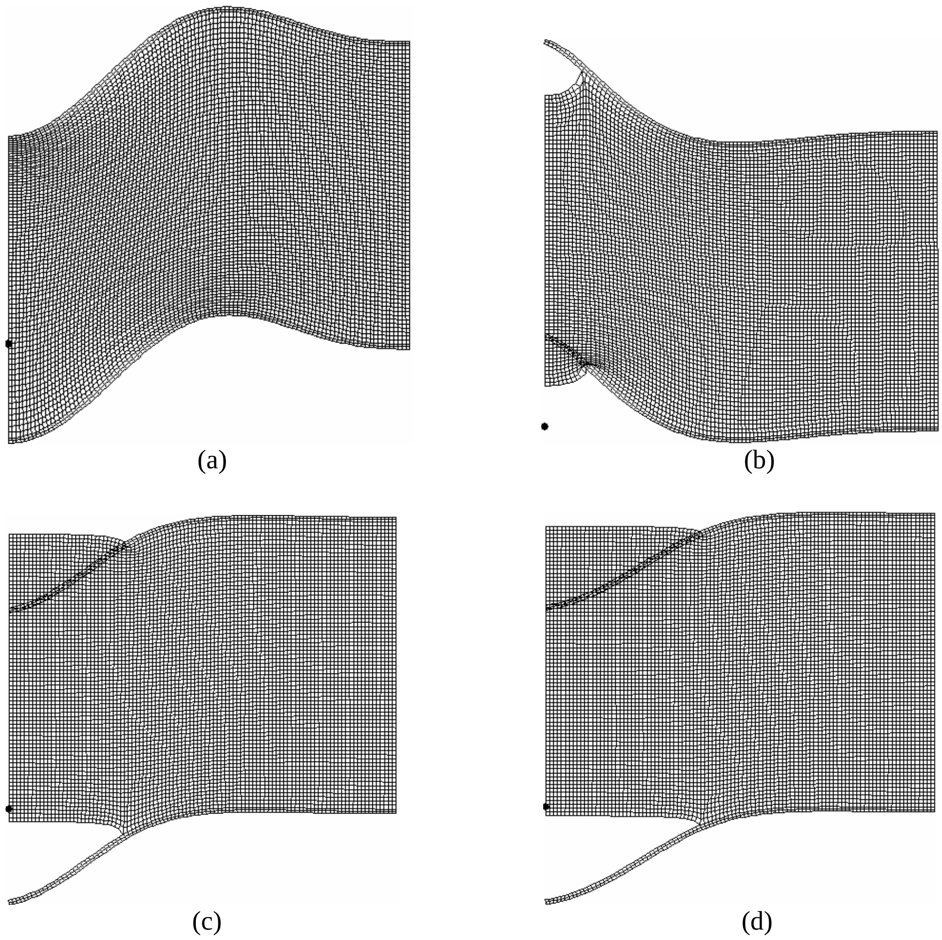


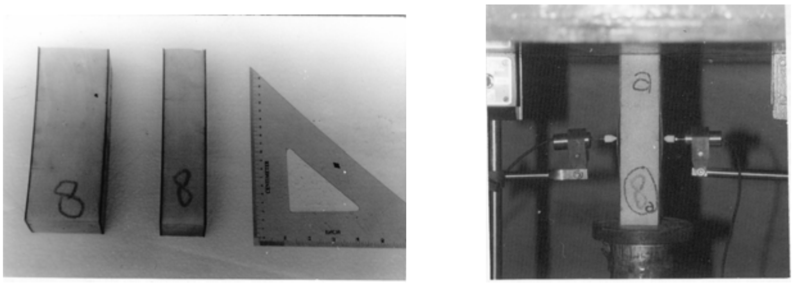
Figure 9 Finite element buckling mode for 75 mm core thickness specimens. (a) without delamination, (b) 10% delamination, (c) 30% delamination, (d) 40% delamination.

Figure 9 shows that specimen having 75 mm core thickness will exhibit wrinkling mode during uniaxial compressive forces. That is especially shown in Figure 9.a, where there is no delamination between the faces and the core. As the delamination length is longer, then the core seems to be motionless, where only the faces shows buckling mode. In this case, the core acts as a foundation for the thin faces to buckle.

Note that for both overall and wrinkling finite element model, only half of the beam specimens were analyzed.

4.2.3 Experimental Results

The experiments were carried out using a compression testing machine. Figure 10 shows the specimens and set up of the experiments. While Figure 11 shows typical load-deflection curve for delaminated sandwich specimens.



(a) (b)

Figure 10 (a) Specimens and (b) Experimental set-up. It two LVDT's and delamination on the specimen.

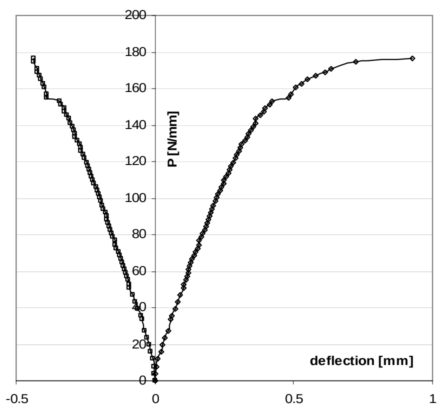


Figure 11 Typical load-deflection curve for delaminated sandwich beams, showing the results of left and right LVDT. Core thickness = 75 mm; delamination length = 20 mm (10%).

4.2.4 Comparison

Table 3 gives comparison between finite element and experimental results for 45 mm core thickness. While Table 4 gives the same results for 75 mm core thickness.

Table 3 Comparison between experimental results and FEM for 45 mm core thickness.

Core thickness [mm]	Delamination length [mm]	Specimen No.	P_{cr} [N/mm]	P_{cr} average [N/mm]	FEM [N/mm]
45	20	1	152.2	144.4	134.0
		2	136.7		
	60	1	54.9	55.4	61.0
		2	55.8		
	80	1	34.8	34.8	43.1

Table 4 Comparison between experimental results and FEM for 75 mm core thickness.

Core thickness [mm]	Delamination length [mm]	Specimen No.	P_{cr} [N/mm]	P_{cr} average [N/mm]	FEM [N/mm]
75	20	1	155.4	160.0	153.1
		2	164.5		
	60	1	59.5	58.1	63.6
		2	56.8		
	80	1	30.4	50.5	44.5
		2	70.6		

Table 3 and 4 shows comparison between experimental results and finite element method for core thickness of 45 and 75 mm respectively. The tables show that the differences are within 10%. Therefore, it can be said that the comparison between the experimental and finite element method in this case is satisfactorily. The two tables also show that by increasing the core thickness by almost double, and thus increasing the beam stiffness, the increase of the buckling load was not as big as expected. Thus it can be concluded, that two different buckling mode occurs. One is overall buckling mode for 45 mm core thickness and the other is wrinkling mode for 75 mm core thickness. This was also shown in Figure 8 and 9.

Figure 12 and 13 show the relations between buckling load and delamination length for 45 and 75 mm core thickness respectively.

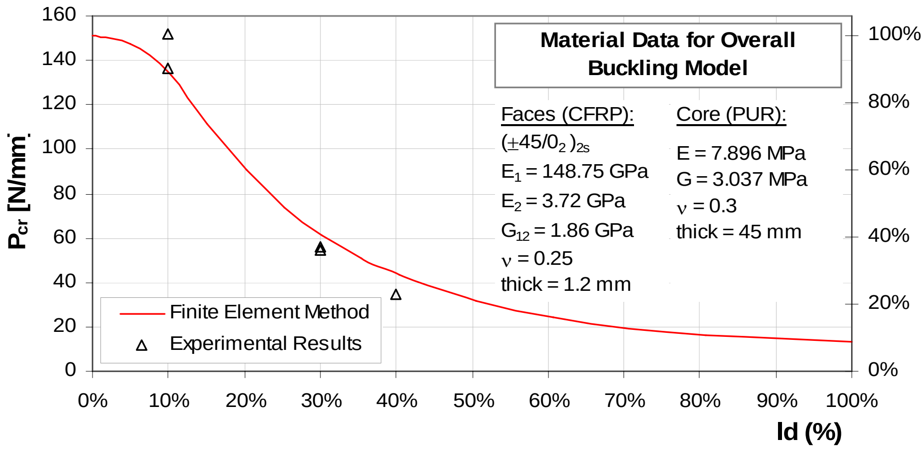


Figure 12 Comparisons between experimental results and finite element method for 45 mm core thickness.

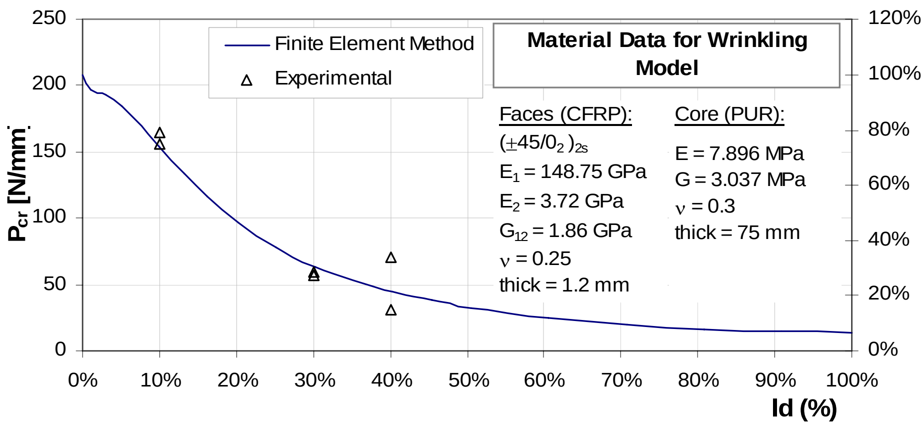


Figure 13 Comparisons between experimental results and finite element method for 75 mm core thickness.

Figure 12 and 13 shows that increasing delamination length will decrease buckling load of the sandwich beams. The steep decreases occur for delamination length between 10 – 40% of the sandwich beam length. For delamination length of less than 10%, the decrease in buckling load is minor, except for wrinkling model, where the decrease can be up to 25%.

The graphs above also show that increasing core thickness will not necessarily increase the buckling loads of the sandwich beams, since sandwich beams having thicker core will exhibit different mode of buckling, namely wrinkling, which will also decrease the capacity of the beam to withstand compressive loads. The existence of delaminated area will further decrease the buckling loads and it shows in Figure 13, it is especially dangerous for wrinkling specimens.

5 Conclusions

The results given in this paper conclude that when we analyze debonded sandwich beams, it is not enough to analyze only a quarter of the beams, as was carried out by Sleight and Wang. The results presented in this paper shows that a quarter model will give misleading buckling loads, since the buckling mode could be in the form of overall buckling mode which is not possible to be analyzed using a quarter model. A half model is the minimum requirement to analyze buckling of sandwich beams.

The paper also shows satisfactory results between experimental data and finite element method for both overall and wrinkling modes of debonded sandwich beams. The differences between these two methods were less than 10%. The results also show that increasing the core thickness will not necessarily increasing buckling loads, since the buckling mode may change from overall to wrinkling modes.

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