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An Experimental Study on Effects of Opening on Buckling of FML Plates Reinforced with Basalt

In this research, effect of opening on the buckling of FMLs (Fiber Metal Laminate) is studied. Samples are made of a laminate, epoxy resin reinforced with four layers of woven basalt fibers, inserted between two Al plates. Different samples are prepared, tested and studied; one group without opening and the other two groups with circular openings of radii 10 and 20 mm. In all samples buckling is associated with de-bonding. Post-buckling behavior is studied. Plasticity in Al plates and damage in composite laminate are detected in samples with opening which make their repair challenging and risky. Nevertheless, repair of samples without opening are straightforward because of the fact that neither of the above phenomena are spotted in these samples.

Keywords: Buckling, Basalt fiber, FML, Opening, Critical Load.

1 Introduction

Fiber Metal Laminate (FML), which is a combination of composite laminate and metal sheets, has received special attention in recent years because of its special features such as its high energy absorption in impact, high fatigue strength and toughness [1-3]. These structures have combined high impact resistance of metals with stiffness of fiber laminates, hence they have most of the benefits of metals and composites together. Moreover, they have a good resistance against humidity and fire compared to fiber laminate composites. Ease of repair and maintenance is another characteristic of FML plates [4-6].

In recent years a great number of researches have been done on the in plane and out of plane static loading and impact on FMLs, but few researches can be found on the buckling of these structures [7-11]. Remmers and De Borst [12] simulated the buckling of FMLs containing a de-bonding numerically. They conclude that the fracture toughness of the de-bonding crack has a considerable effect on buckling. De Cicco and Taheri [13] studied the buckling of FMLs both numerically and experimentally. They did the numerical simulation using 2D and 3D elements and the comparison of load-deformation and absorbed energy from simulation and experiments matched well. Bi et al. [14] studied the buckling and postbuckling behavior of FMLs considering nonlinear geometry and elastoplastic behavior of the metal; in addition, they studied the effects of initial deformation and geometrical parameters on buckling and concluded that initial deformation has a great impact on buckling.

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Effects of prestrain and presence of shape memory wires on buckling of FML plates are studied by Karimlou and Farsani [15]. Their results show that increasing pretension in plates increases buckling load. Several researches on buckling of FMLs are done by Banat et al. [16], Bisagni and Cordisco [17] and Frulloni et al. [18]. Despite the fact that several researches have been done on the buckling of FMLs, we could not find a research on the effect of opening on the buckling of these structures. It is always necessary to create some openings in a plate, therefore it is mandatory to study their effect on the buckling load and even review the postbuckling load to give an understanding of the damage level which helps the repair of these composites. In this paper, the effect of openings on the buckling and postbuckling behavior of FML plates is studied. To perform this study, three samples, one without opening, one with a 10 mm opening and another with 20 mm opening are manufactured and tested.

2 Material and Manufacturing

To make the FML plates, aluminium grade 2024-T3 with thickness of 0.75 mm and laminates reinforced with woven Basalt are used. Woven Basalt has the density of 350 g/m2 and the Epoxy resin is KER 828 which is a Bisfenol-E compound mixed with an Epiclorohydrine hardener. The mixture ratio of resin to hardener is 100 to 10. Aluminium plates, at first are washed with acetone to remove any possible dirt or oil on its surface. Then, they are submerged in alkaline chemicals and finally they are etched to ensure a suitable bonding.

FML plates are composed of two layers of aluminium on bottom and top which have the composite laminate in between. The layup is Al/Ba/Ba/Ba/Ba/Al and thickness is 5mm. In the end, samples are cut to produce test specimens with 100*50 mm dimension. First group of samples has no openings; second group has a circular opening of diameter 10 mm and third group with 20mm diameter opening. All the samples are cut using a water jet system with special nozzle suitable for FML plates. During cutting process water speed is controlled meticulously. At the end of cutting, penetration tests have been done to ensure that there is no crack or de-bonding at the surfaces.

3 Buckling Tests

Buckling tests are done on all 15 samples with an electromechanical universal testing machine brand Hounsfield model H25KS capable of applying up to 25kN force. An edgewise fixture is used to fully clamp (both displacement and slope zero) both ends of the plates, based on ASTM C364-99 standard. Loading rate in all the samples is selected to be 0.5mm per minute. Load- displacement diagram and lateral displacement of each sample is measured and recorded. Axial displacement is measured using a LVDT installed on the machine and lateral deformation is measured with the help of a grid which is attached to the machine frame located in the back of the specimen. During the tests, at some specific points, lateral deformations are measured. A laser light is used to create the image of the edge of specimen on the grid. Moreover, a camera is used to capture high quality images at some instances during test. It is possible to measure lateral deformation based on these images.

3.1 Samples without Opening

Load-deformation diagrams for samples without opening, hereafter called simple samples, are shown in Figure (1) which shows a good repeatability in 5 tests. To study the behavior, the diagram is divided to 4 segments shown by letters A to D. Based on what is shown in Figure (1), each of these four segments are explained in the following.

Linear part: the behavior of this part is linear elastic which start from the start of loading and continues to the start of buckling (point A).

Steep load drop: in this area, as a result of buckling, load decreases (about 3000N) in less than a second, point A to point B.

Gradual decrease: in which load decreases gradually about 1100 N in a 30-40 seconds duration, point B to C.

Level part: in this segment, no special change in load is spotted, point C to the end of experiment.

In linear part, load increases up to about 5200 N (5160 to 5290 in different samples) and after that buckling occurs and the load carrying capacity decreases drastically. Before the buckling, the specimen has no bending and it is completely straight as shown in Figure (2). After buckling, which is associated with de-bonding, one of the Al plates detaches and moves to one side while the laminate and the other Al plate remain attached in their former position with a slight bending. Figure (3) shows one of the samples after buckling at point B. At this point, the bending of the detached Al plate is about 4.8mm and the bending of the two layers which are still together, is about 1 mm. In the next stage, de-bonding develops more and as a result, load carrying capacity decreases and both of the separated parts deform more in lateral direction. Figure (4) shows the specimen at point C. At this point, the bending of the Al plate has increased to 5.9 and that of the two attached layers has become 4.3. In the last stage of diagram, load decreases a few percent, but not considerably.

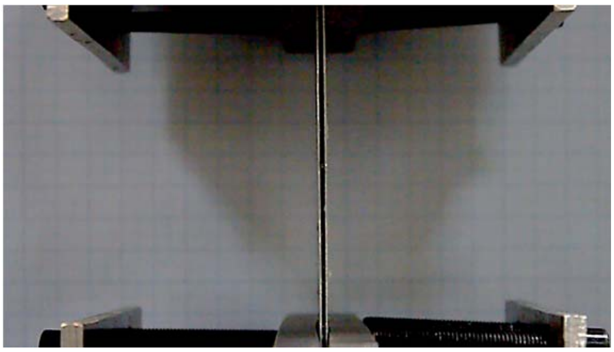


Figure 2 FML plates without opening on the verge of buckling (point A)

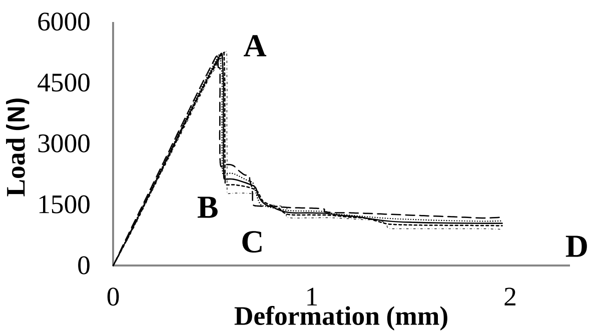


Figure 1 Load-Displacement curves for FML plates without opening.

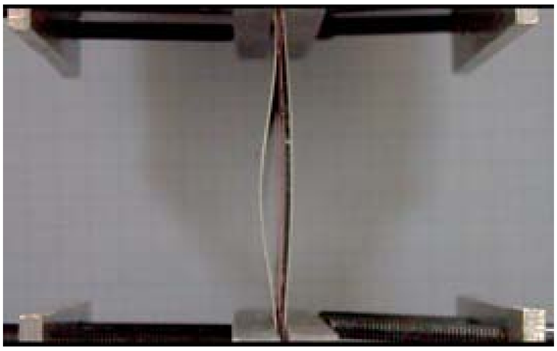


Figure 3 Deformation at load drop due to de-bonding in specimen without opening (point B)

The decrease could be due to local de-bonding in some limited areas. The specimen is shown in Figure (5) at the end of 2mm axial deformation, and as can be seen in this figure, the lateral deformations to left and right are somewhat similar. The bending of the two detached segments are 8.7 and 7.2 mm.

After unloading, no specific permanent deformation is detected in these specimens which means neither did they experienced plastic deformation nor damage in composite laminate.

A sample of unloaded specimen is shown in Figure (6).

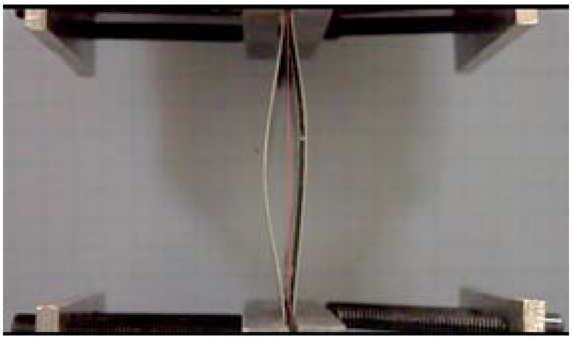


Figure 4 Deformation after second load drop in specimen without opening (point C)

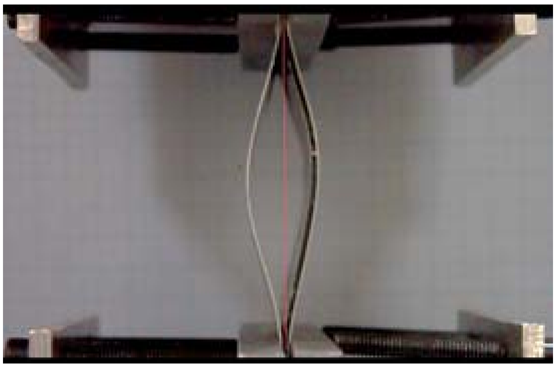


Figure 5 Deformation after second 2 mm compression in specimen without opening (point D)

Figure 6 Specimen without opening after test

3.2 Samples with 10mm Opening

Load-displacement diagrams for samples with 10mm opening are shown in Figure (7), repeatability in these samples are satisfactory. Again, the four segments are shown in these diagrams. The four segments are as follows:

Linear part: the behavior of the part is linear elastic (point A).

Steep load drop: in this area, as a result of buckling, load decreases (about 4900N) in less than a second, point A to point B.

Gradual decrease: in which load decreases gradually between 500N to 1500N in a duration of 10-60 seconds, point B to C.

Level part: in this segment, no special change in load is spotted, point C to the end of experiment. The load is about 900N.

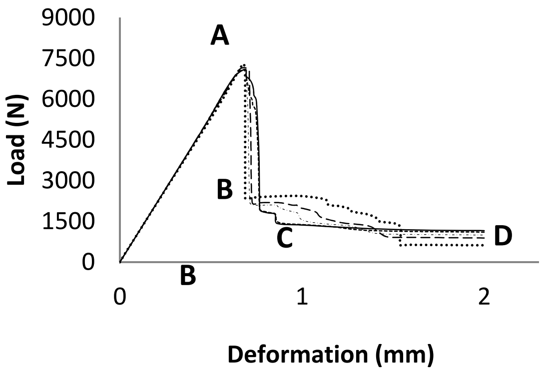


Figure 7 Load-Displacement curves for FML plates with 10 mm opening.

Figure 8 FML plates with 10mm opening on the verge of buckling (point A)

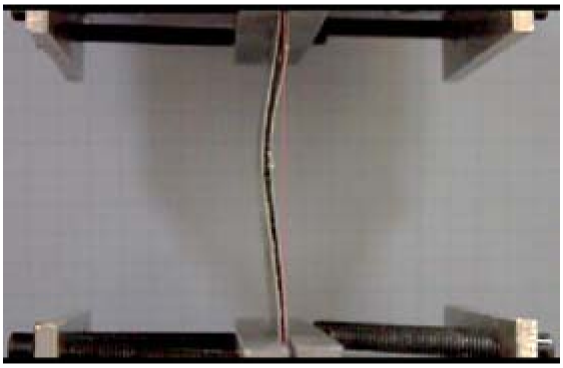


Figure 9 Deformation at load drop due to de-bonding in specimen with 10mm opening (point B)

In the linear part, load increases up to 7100N (7090 to 7120 N) and after that de-bonding and buckling decreases the load severely, the specimen is shown in Figure (8) at this point. As it is expected, no bending can be detected before buckling. As a result of buckling, one of the Al plates become separated from the other parts in a length about half of the length between two grips which occurs near the grips and in the middle of the specimen no de-bonding could be detected in this stage. In this specimen, all the layers bend in the same direction. The sample is shown in point B in Figure (9). At this point, the bending of the midplane is 4.2 mm.

In the next stage, load continues to decrease and de-bonding moves to other areas in a way that in point C, one of the Al plates becomes totally separated and on the other Al plate a local de-bonding occurs (Figure (10)). The maximum bending deformation is increased to 6.86mm. In the last stage, few load decrease is detected in the diagram and lateral deformation increases in this step but no special change in de-bonding area is detected. At the end of this stage, specimen is show in Figure (11), with a maximum bending deformation of 7.7mm. Figure (12) shows the sample after unloading. As can be seen, buckling in this specimen occurs with not only de-bonding but also damage and plasticity. In this point, the remaining bending in the specimen is 1.3mm.

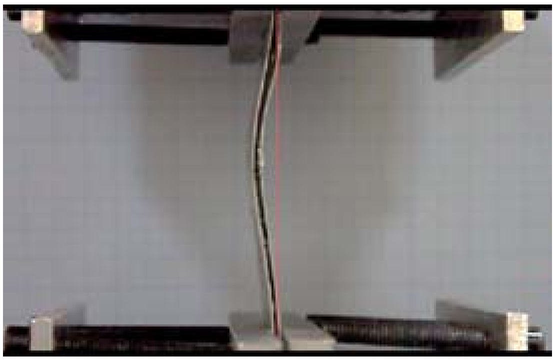


Figure 10 Deformation after second load drop in specimen with 10 mm opening (point C)

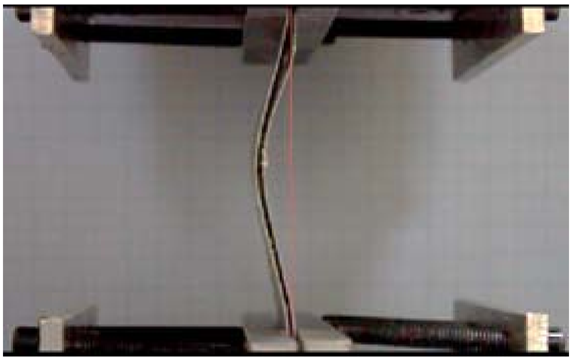


Figure 11 Deformation after second 2 mm compression in specimen with 10 mm opening (point D)

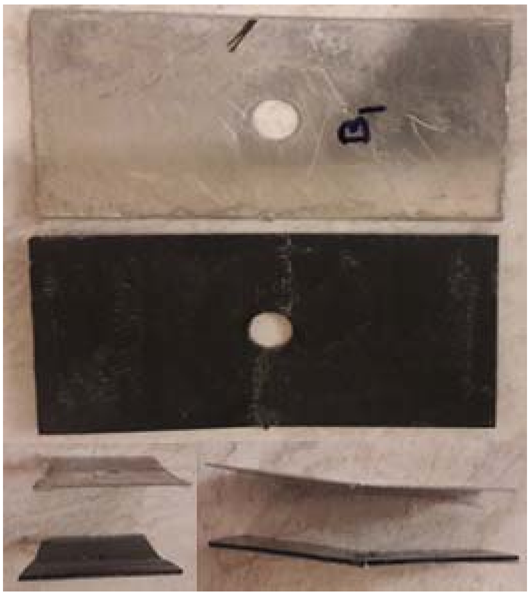


Figure 12 Specimen with 10 mm opening after test

3.3 Samples with 20mm Opening

Repeatability is acceptable in samples with 20mm opening but it is less compared to the previous samples, as shown in Figure (13). Four different regions are as follows.
Linear part: the behavior of the part is linear elastic (point A).

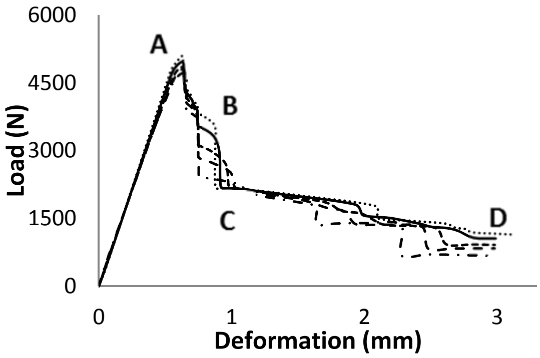


Figure 13 Load-Displacement curves for FML plates with 20 mm opening.

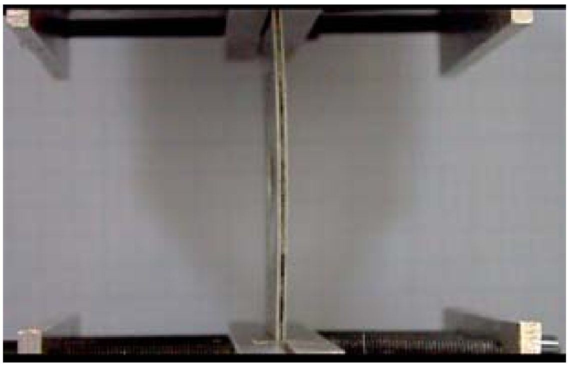


Figure 14 FML plates with 20mm opening on the verge of buckling (point A)

First steep load drop: in this area, as a result of buckling, load decreases (about 1200N) in less than a second, point A to point B.

Second steep load drop: in this area, again, load decreases (about 1300N) in less than a second, point B to C.

Final load drop: in which load decreases gradually to a value between about 1000N and 700N which continues until the end of the experiment.

In the linear stage, load increases up to about 4900 N, varied from 4750N to 5000N, and after that buckling decreases this load. The specimen before buckling is shown in Figure (14). Similar to the other samples, no bending deformation is spotted in this specimen.

By continuing loading, a sudden fall of load occurs that is a result of buckling which is followed by a more slight decrease in load accompanied with deformation. The slight fall may be related to local buckling or damage in composite laminate. Figure (15) shows the specimen in this point, the bending is about 3.2 mm. After that, another huge fall in load occurs which is related to de-bonding. This de-bonding is in mode 2, because no opening can be seen in the specimen. After this decrease, lateral deformation does not change considerably where the bending deformation reaches to 4.5 mm (Figure (16)). In the next stage, load decrease slightly and in some points slight sudden drops of load are spotted. The smooth decrease is related to damage of composite and plasticity of Al plate and the sudden ones are due to growth of de-bonding (Figure (17)). After 2 mm axial compression, maximum bending is 7.2 mm and at the end of 3.3 mm axial compression, this value increase to 9.8 mm. Figure (18) shows the specimen after unloading. The specimen is bent under loading and the remaining bending in this specimen is 5.1 mm.

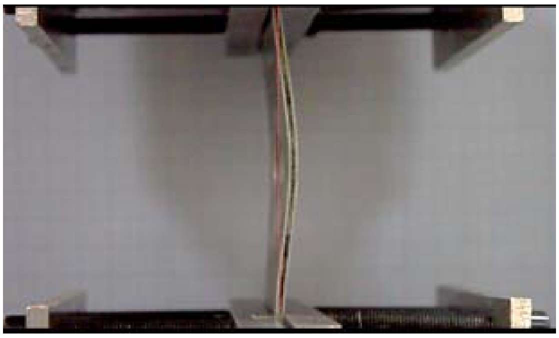


Figure 15 Deformation at load drop due to de-bonding in specimen with 20mm opening (point B)

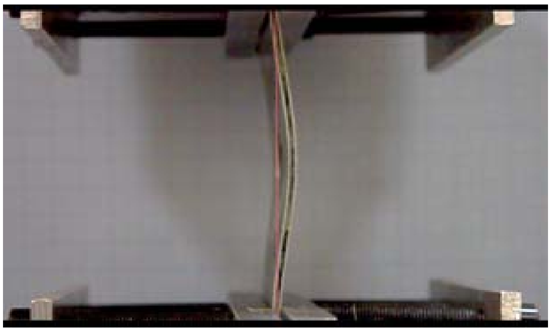


Figure 16 Deformation after second load drop in specimen with 20 mm opening (point C)

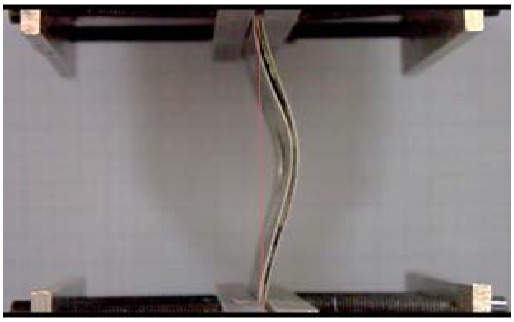


Figure 17 Deformation after second 3 mm compression in specimen with 20 mm opening (point D)

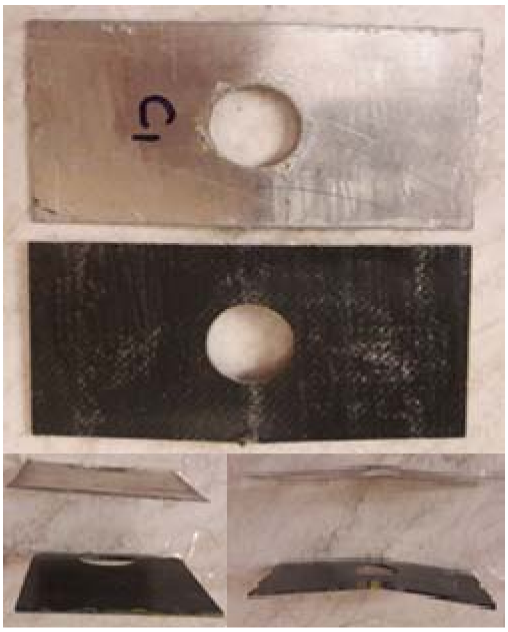
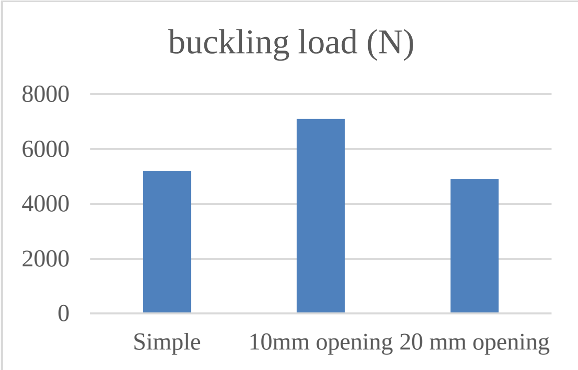
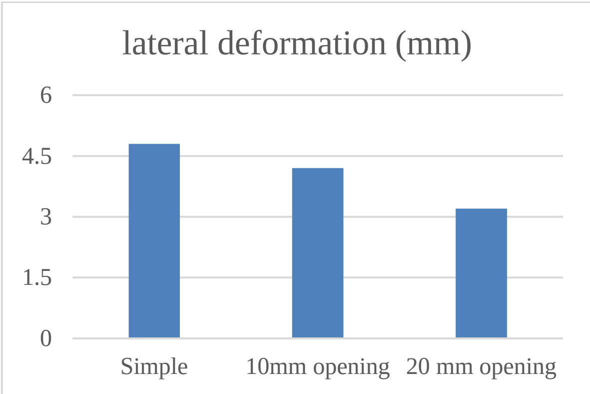


Figure 18 Specimen with 20 mm opening after test



a



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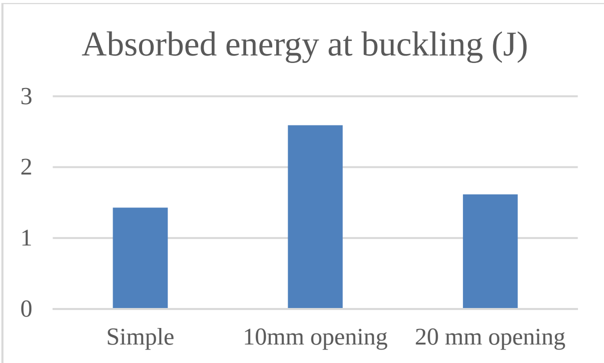

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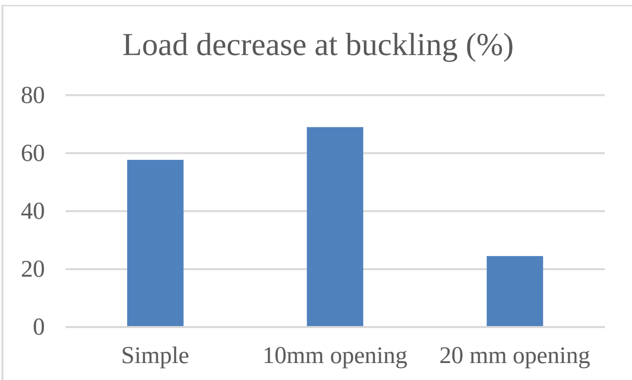

d

Figure 19 Different trends at buckling. a) buckling load (N), b) lateral (bending) deformation immediately after buckling (mm), c) absorbed energy by the specimen before buckling, d) load decrease as a result of buckling (%)

4 Discussion

After tests, results are compared and it shows that three different, yet related, curves are exhibited by these specimens. Figure (19) shows different trends at buckling which are buckling load, lateral (bending) deformation immediately after buckling, absorbed energy by the specimen before buckling, percentage of load decrease as a result of buckling.

In simple specimen, de-bonding and buckling occurs at the same time at a load about 5000N. After de-bonding, one of the Al plates moves to the other side which decreases stiffness of the specimen. Unlike the specimens with opening, the stiffness is the same all over this specimen, so, there is no weak plane to behave like a joint, therefore, de-bonding extends all over the specimen as buckling occurs. The absorbed energy of the specimen at buckling, which is about 1.4 joules, is consumed for de-bonding and bending of the de-bonded parts. Because of the fact that the stiffness of the two parts decreased extremely, lateral deformation is comparatively huge at buckling. Load decrease percentage at buckling in this specimen is 58% which is a big decrease and the reason is buckling and de-bonding which are simultaneous. In sample with 10mm opening, the bending stiffness of the mid-plane is decreased (20% compared to simple specimen) which affects its buckling behavior. After carrying up to about 7000N load, the specimen buckles which is associated with de-bonding. Location of de-bonding is far from the center of the specimen and near the end clamps and its area is much smaller than simple specimen. The ends of the specimen are clamped and the stiffness of the mid-plane is lower comparatively, so the mid-plane behaves like a joint and buckling occurs. At the same time the bending in clamp location increases severely, therefore, de-bonding occurs because bending stiffness of the Al plate and composite laminate are different. This specimen absorbs more energy before buckling.

In this specimen, de-bonding is limited and after buckling both Al plates and composite laminate bends in the same direction, so buckling occurs in a higher load and the specimen absorbs more energy till buckling. This energy is consumed to bend specimens and create de-bonding cracks locally. As mentioned, de-bonding is limited in this specimen, so loss of stiffness is less compared to simple specimen; therefore, lateral displacement is lower. In this specimen, load decreases from 7000N to 2100 N, which is about 69% decrease in load which is the maximum decrease in three different geometries which are tested. It shows the severity of buckling which is associated with de-bonding.

In sample with 20mm opening, the bending stiffness of the mid-plane is less compared to the other two (40% less than simple specimen and 25% less than specimen with 10 mm opening). This decrease changes the buckling behavior. Mid-plane behaves like a hinge and specimen buckles under a load of about 4900N with almost no de-bonding. This load is less than that of the other two specimens because the minimum section area is reduced extremely. Yet, absorbed energy at buckling is more than the simple specimen, because of the fact that no de-bonding occurs and whole the body bends together after buckling. The first steep load decrease in this specimen is 24% that is clearly less than the other two specimens because de-bonding does not occur in this stage. Short after that a 26% sudden decrease occurs which is a result of de-bonding. At this stage, the amount of total load decrease is 51%, which is near to the decrease percentage in simple specimen. After buckling, load decrease is limited and related to some growth in de-bonding crack. It is not a ductile crack growth; hence each step of growth is accompanied by a sudden small fall of the load. After buckling, bending increases which is totally elastic and reversible, as shown in the picture of samples after unloading. In specimen with 10mm opening, after buckling, some growth in de-bonding causes small sudden falls in load; Moreover, plasticity and damage growth cause a smooth decrease in load. All of these three phenomena happens together after buckling in this specimen. A similar situation exists in sample with 20 mm opening, the only difference is related to the rate of decrease which is more in the specimen with 20mm opening.

It is related to weaker midsection. In samples with opening, after buckling, plastic deformation and damage are occurred which is really important from a repair point of view. Although the simple specimen buckles sooner, after 2mm axial compressive deformation, the composite laminate remains undamaged and no plastic deformation occurs in Al plates, therefore, it is possible to repair this composite completely by simply injecting adhesive between layers. In samples with opening, there is a high probability of plastic deformation and damage; as a result, it is not possible to repair them completely.

5 Conclusion

Buckling tests are done on FML samples without opening and with 10 and 20 mm openings. Four specific parts can be detected in all load-deformation diagrams which include linear behavior followed by a sharp load decrease which is a result of buckling and de-bonding. De-bonding is detected in all the specimens. Maximum load carrying capacity and maximum load drop are detected in sample with 10 mm opening and the minimum one is spotted in the sample with 20mm opening. In later stages de-bonding grows and detaches one of Al plates and load decreases to 1000 N or lower. The following points are the main results:

- Introduction of hole to the composite tested does not always decrease the critical load. Critical load, and accordingly maximum deformation at buckling, occurs in sample with 10 mm opening; moreover, this specimen absorbs the highest energy at buckling compared to the others.
- Largest lateral deformation at buckling is related to the sample without opening in which all the sections have the same area.
- Plasticity in Al plates and damage in composite laminate are detected in samples with opening which makes their repair a hard work. In the end, neither damage nor plasticity are detected in simple specimen, which makes the repair easier, safer and more reliable.

Acknowledgments

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References

[1] Vlot, A., and Gunnink, J., "*Fibre Metal Laminates – An Introduction*", First Edittion, Kluwer Academic Publishers, Dordrecht, Nederland, pp. 17-28, (2001).

[2] Fan, J., Cantwell, W., and Guan, Z., "The Low Velocity Impact Response of Fiber-metal Laminates", Reinforced Plastics and Composites, Vol. 30, pp. 26-35, (2011).

[3] Tsartsaris, N., Meo, M., Dolce, F., Polimeno, U., Guida, M., and Marula, F., "Low Velocity Impact Behavior of Fiber Metal Laminates", Composite Materials, Vol. 45, pp. 803-814, (2011).

[4] Sadighi, M., Pamanen, T., Alderliesten, R., Sayeaftabi, M., and Benedictus, R., "Experimental and Numerical Investigation of Fiber Metal Laminates", Applied Composite Materials, Vol. 19, pp. 545-559, (2012).

[5] Naik, N., Asmelash, A., Kavala, V. R., and Ch, V., "Interlaminar Shear Properties of Polymer Matrix Composites: Strain Rate Effect", Mechanics of Materials, Vol. 39, pp. 1043-1052, (2007).

[6] Ghasemi, F. A., Firozjaei, E. A., and Anaraki, A. P., “An Experimental Study of Temperature Effect on Low Velocity Impact Response of Notched Aluminum Plates Repaired by FML Composite Patches”, Modares Mechanical Engineering, Vol. 14, pp. 175-182, (2014).

[7] Vermeeren, C., “A Historic Overview of the Development of Fibre Metal Laminates”, Applied Composites Materials, Vol. 10, pp. 189-205, (2003).

[8] Alderliesten, R., Rans, C., and Benedictus, R., “The Applicability of Magnesium Based Fibre Metal Laminates in Aerospace Structures”, Composites Science and Technology, Vol. 68, pp. 83-93, (2008).

[9] Cantwell, W.J., and Morton, J., “Impact Perforation of Carbon Fibre Reinforced Plastic”, Composites Science and Technology, Vol. 38, pp. 19-41, (1990).

[10] Zhu, S., and Chai, G.B., “Low Velocity Impact Response of Fibre-metal Laminates Experimental and Finite Element Analysis”, Composites Science and Technology, Vol. 72, pp. 793-802, (2012).

[11] Sadighi, M., Alderliesten, R.C., and Benedictus, R., “Impact Resistance of Fiber-metal Laminates: A Review”, International Journal of Impact Engineering, Vol. 49, pp. 77-90, (2012).

[12] Remmers, J. C., and De. Borst, R., “De-bonding Buckling of Fibre-metal Laminates”, Composites Science and Technology, Vol. 61, pp. 2207- 2213, (2001).

[13] De Cicco, D., and Taheri, F., “Robust Numerical Approaches for Simulating the Buckling Response of 3D Fiber-metal Laminates under Axial Impact-validation with Experimental Results”, Journal of Sandwich Structures & Materials, Accepted for Publication, DOI: 10.1177/1099636218789614, (2018),

[14] Bi, R., Fu, Y., Tian, Y., and Jiang, C., “Buckling and Postbuckling Analysis of Elasto-plastic Fiber Metal Laminates”, Acta Mechanica Solida Sinica, Vol. 27, pp. 73-84, (2014).

[15] Karimlou, M. M., and Farsani, R. E., “Influence of Prestrain and Position of Shape Memory Alloy Wire on Buckling Properties of Smart Fibers Metal Composite”, Modares Mechanical Engineering, Vol. 17, pp. 429-436, (2018).

[16] Banat, D., Kolakowski, Z., and Mania, R. J., “Investigations of FML Profile Buckling and Post-buckling Behavior under Axial Compression”, Thin-Walled Structures, Vol. 107, pp. 335-344, (2016).

[17] Bisagni, C., and Cordisco, P., “Post-buckling and Collapse Experiments of Stiffened Composite Cylindrical Shells Subjected to Axial Loading and Torque”, Composite Structures, Vol. 73, pp. 138-149, (2006).

[18] Frulloni, E., Kenny, J., Conti, P., and Torre, L., “Experimental Study and Finite Element Analysis of the Elastic Instability of Composite Lattice Structures for Aeronautic Applications”, Composite Structures, Vol. 78, pp. 519- 528, (2007).