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Practical Approaches of Inducing Controlled Simulated Resin Starvation Areas into Vacuum Infusion Processed Sandwich Composites Used for Characterisation of the Surface Defects and their Outcomes

Abstract

Manufacturing defects in the sandwich structures have significant impact on their ultimate strength performance. It is essential to codify some criteria for the effects of such defects on the performance of the structure in order to investigate the quality of sandwich compo-sites and their load-bearing capabilities. By means of such criteria, one can predict the property degradation of the defected structure in comparison to a defect-free one, and assess whether the faulty part could be remained in the structures. Among all the potential defects in a sandwich structure they could be induced during the Vacuum Infusion Process (VIP), the dry area defect is the most significant and frequently occurring one. Hence, adequate tests should be conducted in order to examine the effect of dry area defect on the structure. For this purpose, a methodology is required for preparing the defected samples similar to the main structure. The current study is aimed at suggesting two accurate approaches to induce artificial defects in sandwich structures manufactured implementing the vacuum infusion process. These methods are used for making some defected samples and their responses are compared with those of the defect-free structures. All samples are subjected to the uniform inplane compression loading and their behaviors up to the fracture point are evaluated to assess the remaining strength. Infusion process.

Keywords

dry area defect; sandwich composite; vacuum infusion process (VIP); in-plane compression.

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1 INTRODUCTION

1.1 Statement of the Problem

The fiber-reinforced polymer composites are widely used in many industrial applications. Compression molding in Ren (2016) and Graupner (2016) researches, liquid molding (Barari (2016)), injection molding (Wang (2016), Feldmann (2016), Teixeira (2016)) and vacuum infusion (Gu (2014), Mendibil (2016)), are common methods for manufacturing the polymer matrix composites (PMCs). In all above-mentioned manufacturing techniques, defects in the matrix, fibers or interface would be unavoidable. Matrix defects might be in the form of incomplete curing and voids; fiber defects could be misalignments, waviness and broken fibers and irregularities of fiber distribution in the matrix; and the interfaces could suffer from delamination (Phil (2014)). Defects can also inadvertently be produced in the course of the normal service life of the components (Brad (2013)).

Among the composite structures, sandwich composites have great properties making them ideal for many structural applications, especially the marine ones. The manufacturing process for these structures has certain techniques, which must be applied carefully. Vacuum Infusion Process (VIP) is placed among the advanced methods of composite structure processing, which if applied correctly would produce sandwich structures with great strengths and low weights.

Resin starvation is known as a major defect in the vacuum infusion composite manufacturing process that would result significant loss of mechanical properties in final product. During VIP processing, resin flows from infusion veins towards the vacuum pipes. The vacuum pressure is the driving force for the resin motion in this process there might be some misconfiguration that would result in loss of vacuum pressure in a limited area. Resin won't flow through the areas where there is no vacuum pressure. Thus, there would be a resin starved area in the final product.

Based on above descriptions, there is a need to establish the damage tolerances and repair criteria for the defected structures. Studies performed in the UK to establish the damage tolerances of stiffened single-skin GRP ship structures are reported by Sumpter et al. (1997) and by Elliott and Trask (2001). They have enabled repair criteria to be established for the Royal Navy's Hunt Class vessels. These repair criteria need to be backed up with sufficient experimental data to assess an efficient repair procedure based on a specific defect. The data includes the strength reduction characteristics based on the geometrical parameters of the defects. In other words, characterisation of the defects and their outcomes is inevitable.

1.2 Selection of Previous Work on Characterisation of the Surface Defects and their Outcomes

Fotsing et al. have done a research on characterization of surface defects based on surface deflectrometry Fotsing (2014). The basis for such study is to devise an effective method to artificially embed controlled defects into the structure. The controlled defects make it possible to characterize their properties and study different structural parameters such as deformation and strength. Another example of the works on characterization of the defects is performed by Sorrentino et al., where a new methodology to evaluate the influence of curing overheating on the mechanical properties of thick FRP laminates is introduced (sorrentino (2017)). Przemysław (2016) also studied characterization of the defects in curved composite structures using active infrared thermography. In his re-

search, artificial controlled delamination defects were embedded into the FRP composites with teflon films, (Przemysław (2016)).

Yokozeki et al. (2013) proposed a property control method in vacuum-assisted resin transfer molding (VARTM) using porous mold process (PMP) to fabricate carbon fiber-reinforced polymer composites. The effect of infused resin content on the final mechanical properties of CFRP was investigated and it was demonstrated that volume fraction of carbon fibers and the resultant mechanical properties of CFRP can be controlled by the infusion process control.

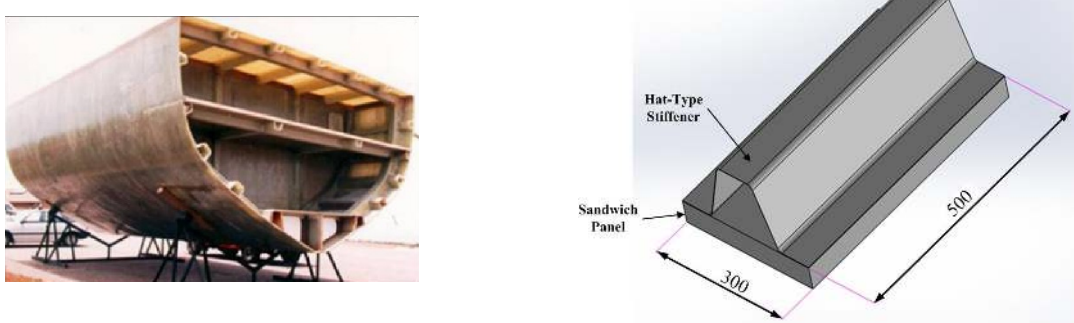
1.3 Necessity of the Present Work and its Outlines

To the authors' knowledge, there is no similar study to devise a practical procedure to embed controlled zone of artificially induced resin starvation defect in sandwich panels during vacuum infused process (VIP). That is why, in this study, two practical approaches to artificially embed resin starved area in vacuum infusion process are introduced. The specimens considered in the current study are elements of a composite main hull that has hat-shaped stiffeners. The stiffeners are applied to the interior of the structure in order to increase the bending strength of the main hull. Mechanical behavior of the specimens with embedded defects is compared with that of the naturally-defected specimens under uniform in-plane compression according to the ASTM D7137 Test method(2012).The proposed approaches can simply be employed in later experimental or even numerical simulations in order to establish reliable damage tolerances and repair criteria for the defected composite structures.

2 EXPERIMENTS

2.1 Geometry of the Specimens and Mechanical Properties of their Constituents

The 300 mm×500 mm rectangular sandwich composite panel specimens were prepared with identical materials and process conditions. The panels are stiffened with a laminated hat-shaped stiffener commonly used in construction of composite ship hulls, according to Figure 1. Detailed geometry and dimensions of the specimens along with the location of the defect area are all illustrated in Figure 2.



(a) (b)

Figure 1: (a): Composite hull section reinforced with hat-shaped stiffeners;
(b): Specimen geometry as an element of actual main hull.

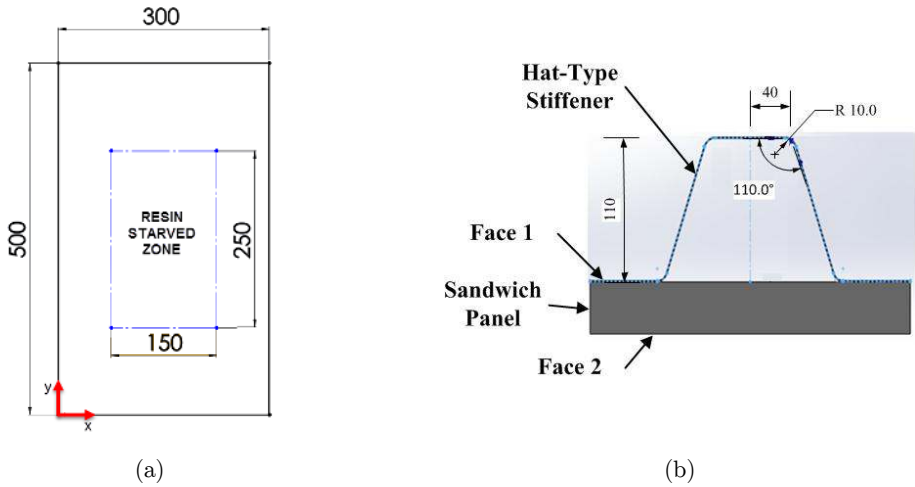


Figure 2: (a): Geometry of the test specimen (viewed from the back) and location of the embedded defect; (b): Sectional view of the sandwich panel and attached stiffener (dimensions in mm).

The specimens were manufactured using Vacuum Induced Process (VIP). The vinyl ester resin induced under the vacuum pressure, according to the lay-up design given in Table 1. In Table 2 the material properties of composite laminates are presented. For each specimen, a region with the dimensions of 150 mm×250 mm , i.e. 25% of the total area, was devoted to the resin starved surface (Figure 2). Resin starvation usually occurs on one side of the specimens, where resin flow finds a shortcut towards the vacuum pipes. Thus, the artificial starvation defect is embedded only on one side of the specimens and the other face is perfectly constructed and stiffened.

	Layer No.	Thickness (mm)	Description
	1		$G^{*}(+45^{\circ})/K^{**}((+45^{\circ})/G(90)/G(-45^{\circ})/ K(-45^{\circ})/M^{***}$
	2		$G(0^{\circ})/G(90^{\circ})$
FACE 1	3	3.5	M150
	4		$G(0^{\circ})/G(90^{\circ})$
	5		M225
CORE		30	H80 PVC Foam
	6		$G(+45^{\circ})/K(+45^{\circ})/G(90)/G(-45^{\circ})/ K(-45^{\circ})/M150$
	7		$G(0^{\circ})/G(90^{\circ})$
FACE 2	8	3.5	M150
	9		$G(0^{\circ})/G(90^{\circ})$
	10		M225
Stiffener		1	$CSM150/C^{****}400/ CSM150/ CSM150/G200/ CSM150$
			* Glass woven fabric
			** Kevlar woven fabric
			*** Glass Mat
			****Carbon woven fabric

Table 1: Lay-up plan for the tested sandwich panel specimens.

WR Ply (0-90)	Woven E-Glass (G)	Glass Mat(M)	WovenKevlar (K)
Ex(GPa)	15.34	8.7	31.23
Ey(GPa)	15.34	8.7	31.23
G (GPa)	5.14	3.42	5.23
υ	0.30	0.28	0.36
Sx (MPa)	186	186	123
Sy (MPa)	186	186	123
Ss (MPa)	45	45	65

Table 2: Material properties of the composite laminates.

2.2 Preparing Specimens with Artificial Resin Starved Defect

As previously mentioned, in current research two practical approaches were proposed and investigated for inducing artificial resin starved defect in the sandwich structures. The load-carrying capacity in composite materials is highly dependent on the matrix-fiber bonding quality. Therefore, if the fibers are not filled with sufficient amount of resin in a certain region during the manufacturing process, a starved area without the load carrying capability would be produced. This region has no significant mechanical properties and could be neglected during simulation and analysis of the structure.

2.3 Elimination of the Fibers Before Resin Infusion Process (Plan 1)

In the first method, no laminate is applied in the region that is considered as the dry area. For this purpose, the fibers are removed from the structure with respect to dimensions of the dry area, and then the resin is infused into the structure (Figure 3).

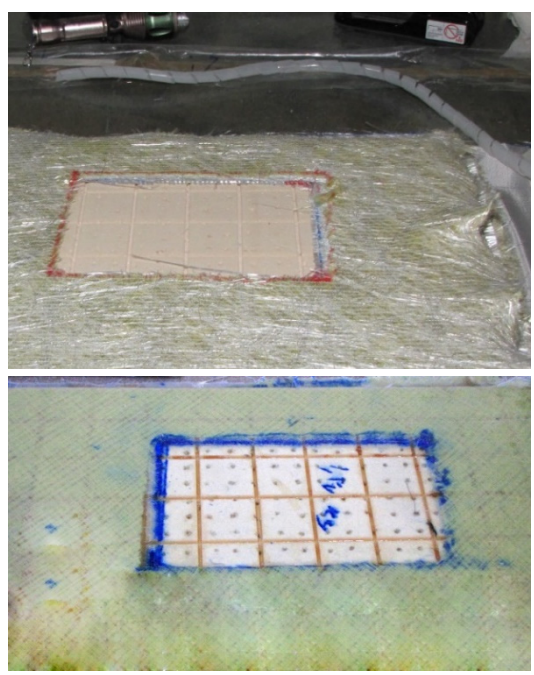


Figure 3: Defected specimen prepared according to the plan 1.

2.4 Elimination of the Fibers After Resin Infusion Process (Plan 2)

In plan 2, the specimen is produced completely with descent integrity after complete resin infusion, the panel is let to dry and finish the curing process. A rectangular area with certain dimensions is machined on the structure up to the desired depth with special instruments (Figure 4).



Figure 4: Steps of preparing the defected specimen according to the plan 2.

2.5 The Sample with a Natural Starved Area Defect Induced During the Manufacturing Process (Plan N)

For comparison of the proposed methods, some specimens with natural dry area were also prepared. For this purpose, a vacuum tube was located at the center of the specimen as shown in Figure 5, and once the resin is filled the panel in an approximated desired dimensions, the resin infusion tubes were cut and the resin was allowed to be cured.

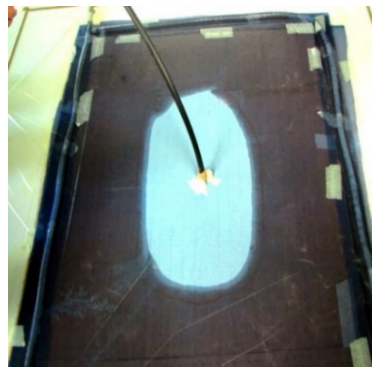


Figure 5: Specimen with naturally-induced dry area defect during the manufacturing process.

2.6 Test Setup and Boundary Conditions

The samples prepared according to plans 1, 2 and N were subjected to uniform in-plane compression, and their elastic behaviour prior to the fracture were compared to each other. The test rig consists of two vertical towers dimensioned to withstand the horizontal forces originating from the Poisson's effect when the panel is compressed in the vertical direction. The forces are thus transferred into the underlying bottom plate. The connection between the towers and the bottom plate is effected by four adjustment devices, where they are able to adjust the horizontal distance between the towers and make it possible to test the panels with varying breadths. Furthermore, four vertical and adjustable steel ribs ensure that the panel edges are not able to move in the out-of-plane direction. Teflon tape is attached to the inside of the ribs, thus limiting friction between the panel and steel ribs. Finally, the loading is introduced by use of a horizontal steel beam attached to the test machine. The horizontal steel beam is specially shaped to be able to slide down between the steel ribs. The position of the beam can furthermore be adjusted in the out-of-plane direction. Such a test method covers compressive residual strength properties of multidirectional polymer matrix composite laminated plates. The test setup is shown in Figure 6. A special fixture was designed for performing the tests in order to satisfy the boundary conditions depicted in Figure 7.

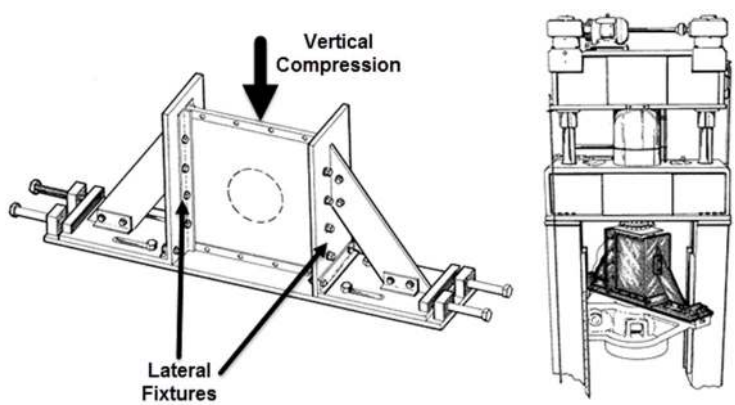


Figure 6: Test setup for applying the uniform compression on the specimens.

	Boundary's ID Number			
	4	3	2	1
Boundary Conditions	Ux=0 Uy= Free Uz=0 ϑx=0 ϑy=0 ϑz= Free	Ux=0 Uy=0 Uz=0 ϑx=0 ϑy=0 ϑz=0	Ux=0 Uy= Free Uz=0 ϑx=0 ϑy=0 ϑz= Free	Ux=0 Uy=Free Uz=0 ϑx=0 ϑy=0 ϑz= Free

Ux: Displacement along x-axis
Uy: Displacement along y-axis
Uz: Displacement along z-axis
ϑx: Rotation about x-axis
ϑy: Rotation about y-axis
ϑz: Rotation about z-axis

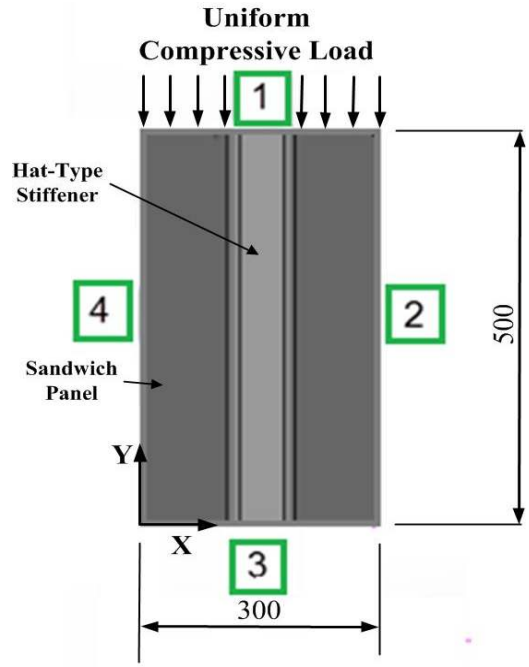


Figure 7: Boundary conditions for the tested specimens (dimensions in mm).



Figure 8: Designed fixture put inside the universal testing machine.

3 EXPERIMENTAL MEASUREMENT AND TEST EQUIPMENT

In order to measure the average in-plane strain in vertical direction, unidirectional strain-gages were installed on the plane midline. TML UBF series unidirectional strain gages were applied on the specimen's intact surfaces. These Strain gages are specialized to measure the strain on the composite structures. The specimens were tested by installing the specialized fixture within a Shimadzu Autograph AG-25-TC universal testing machine with a loading capacity of 250 kN (Figure 8). The tests are performed in a displacement control mode, while the accuracy of the load cell is validated in conjunction with the tests so that it proves to be fairly accurate even for relatively limited forces below 10% of the maximum capacity. Values of the in-plane force exerted in vertical direction on each specimen and induced shortening are recorded as well as the average strain.

4 RESULTS AND DISCUSSIONS

Two specimens labeled as A and B were prepared for each of the plans. Based on the test results, the average in-plane strain in vertical direction (ε_y) is plotted in terms of the vertical shortening (ε_y), as shown in Figure 9. Considering the nature of loading and the magnitude of deformations, the cross–section of the specimen could be assumed constant so the average stress on the specimen could be calculated by dividing the measured force on the cross-sectional area. The relationship between the average in-plane stresses in vertical direction (ε_y) versus the average in-plane strain in vertical direction (ε_y) for all of the specimens are also plotted in Figure 10.

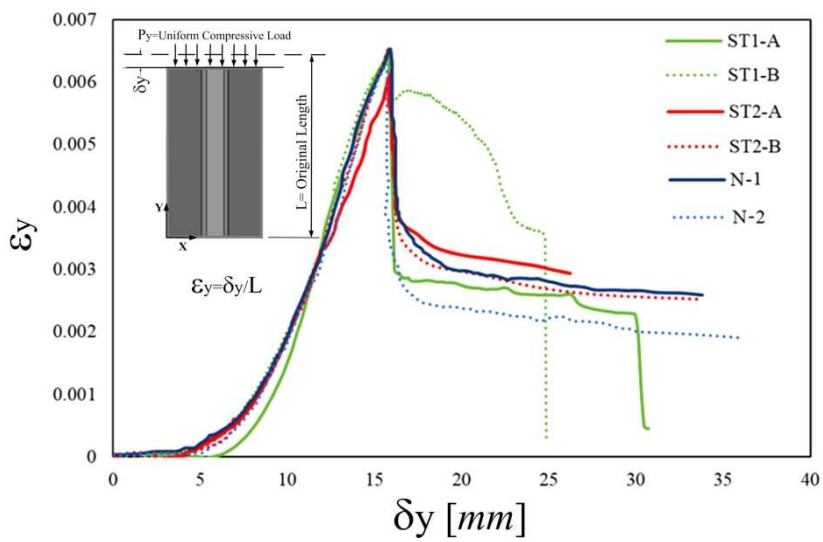


Figure 9: Relationship between the average in-plane strain in vertical direction (ε_y) and vertical shortening (ε_y) for all specimens.

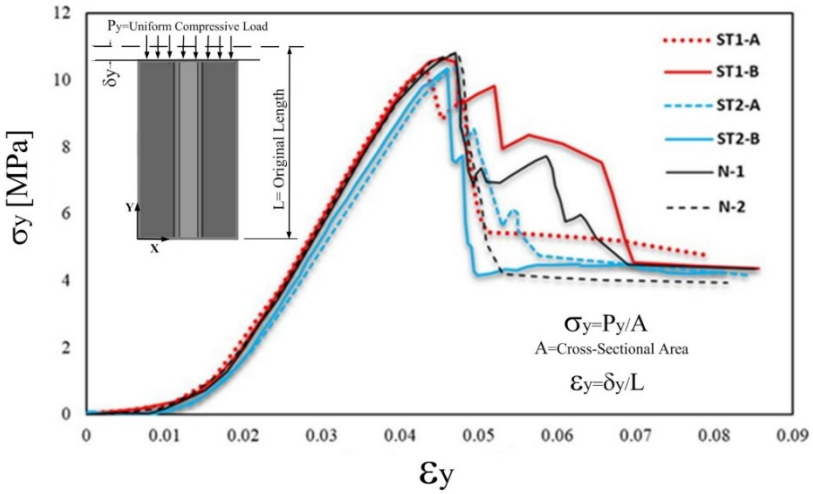


Figure 10: Relationship between the average in-plane stress in vertical direction (σ_y) and the average in-plane strain in vertical direction (εy) for all specimens.

Experimentally measured values of the applied load on the top edge of the specimens, corresponding average in-plane stress in vertical direction in addition to the vertical shortening of specimens and also their compressive modulus in elastic range are all given in Table 3. Furthermore, fracture modes are shown in Figure 11 for all of the specimens.

Defect Inducing Plan	Specimen Code	Compressive Modulus E_c (MPa)	Stress σ (MPa)	Load F_{max} (kN)	Deflection of the Top Edge d_{max}(mm)
Plan 1	ST1-A	353	10.270	114	13.0
	ST1-B	360	10.631	118	13.6
Plan 2	ST2-A	343	10.360	115	14.2
	ST2-B	361	10.327	115	13.8
Naturally-generated Dry Area	N-1	368	10.811	120	14.1
	N-2	373	10.811	120	14.2

Table 3: Values of the load, stress and deflection of the top edge, and the compressive modulus at the ultimate point.

As is evident from the figures, the proposed plans could exhibit a behavior similar to that of the samples with natural dry area. The main goal of this study is to produce structures with artificial defects that behave almost as a natural structure in the elastic region. Among the proposed plans, ST1 specimens constructed based on the plan 1 exhibited better similarities to the real cases. As it can be seen in Figure 11, area of the dry region in the naturally defected specimen is slightly smaller than that of the dry region in artificially defected specimens. Study of the area's boundary conditions reveal the fact that stress concentration is slightly lower in the case of the naturally defected specimens. This matter would of course result in some differences in the ultimate load level before the specimens fail in compression.

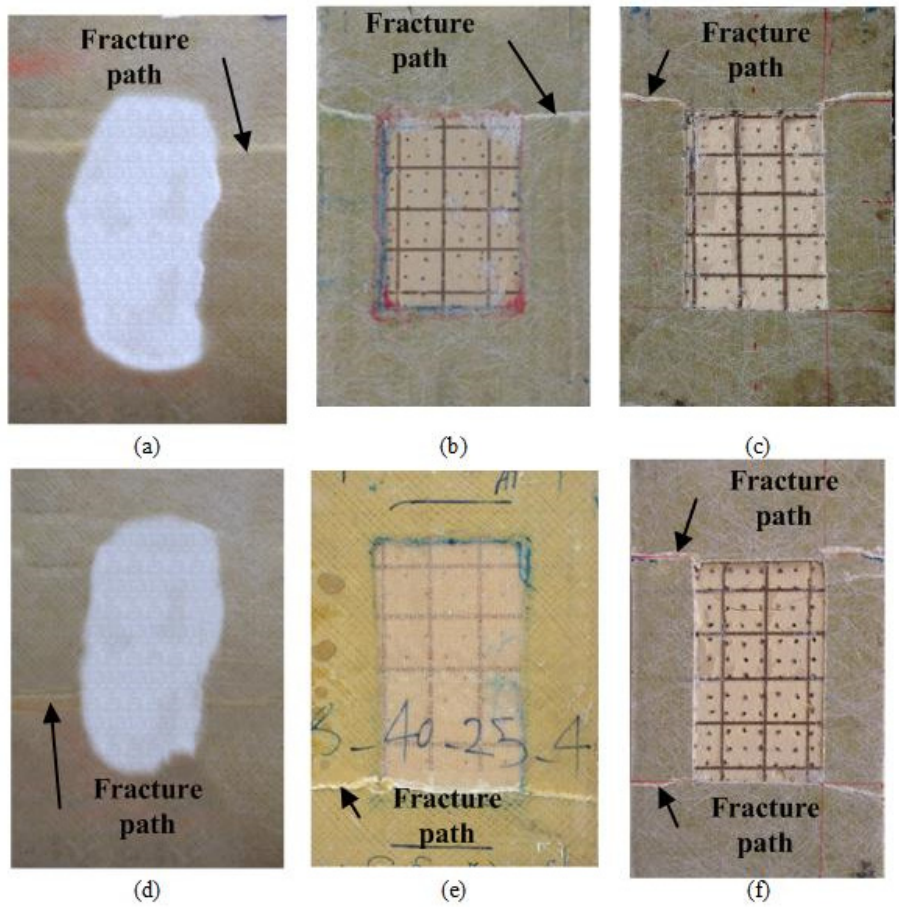


Figure 11: Comparison of the fracture modes for the tested specimens:
(a) and (d): plan N; (b) and (e): plan 1; (c) and (f): plan 2.

Mechanical properties of the defected structures were also determined. As can be confirmed, properties such as the Young's modulus, maximum compressive stress and the ultimate load of the defected specimens are consistent with those of the naturally defected specimens. Hence, all the proposed plans for manufacturing artificially defected specimens could be practically employed for investigation of the mechanical properties of the defected structures. Delamination of the face sheet and core was the main considerable failure mode in the specimens. The failure mechanism and failure load in all instances were similar. However, the behavior of the structures after failure was different because of the foam shattering at the lading point, as well as many non-linear parameters involved in the fracture mechanics of the specimens.

5 CONCLUSIONS

In this study, two methods were proposed for inducing artificial dry area defect in the sandwich structures. The conformity of proposed plans with reality for in-plane loading was evaluated using the uniform compression test. Specimens were prepared in vacuum infusion process with the same

materials, stacking sequence and production conditions. Behaviour of specimens with artificially embedded defects were compared with that of naturally defected specimens having the same size and material properties. Based on the experimental results, the proposed methods could be successfully utilized in order to induce the artificial dry area defect in the structures. With such a capability, it would be possible to conduct more accurate experiments and further investigate the impact of dry area defect on the mechanical properties of the composite structures. Among all the suggested plans, the ST1 case was observed to have highest similarity to the natural instances. Also, if application of the methods is considered with the proposed plans, then resin starvation defects in certain number of layers could be well simulated. In other words, in the plan 1 method the number of layers that should be located in the starved area can be eliminated in the stacking sequence and then the lay-up may be performed without those layers. Similar condition could be simulated in the plan 2 in which the laminate could be mechanically removed up to a certain depth with accurate machining. Plan 2 would generate district separation lines on the designated resin starved zone which has multiple micro cracks that could be an appropriate zone of failure initiation. On the other hand, the defected area in the plan 1 is smoothly bonded to the rest of structure and there are no micro cracks present in that zone. An advantage of plan 1 over plan 2 is that more complex dry area geometries can be generated while the plan 1 is practically limited to simple shapes. This difference must be taken into consideration before employing the proposed methods.

In this research two innovative approaches were introduced that could make it possible to embed controlled defects in composite sandwich specimens. These controlled defects may be used in further studies to characterize the effects of resin starvation defects on the strength of cored sandwich composite structures.

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