

Ultimate Strength of Stiffened Composite Plates with Large Opening

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Abstract—The corrosion of steel is the main problem in stiffened steel plated structures in bridge decks, ship structures and offshore oil platforms. Fiber reinforced polymer composite stiffened plates can be used as an alternative to steel plated structures due to its corrosion resistance, fatigue strength and high strength and stiffness to weight ratio. Large openings are provided in the plated structures for access and service, and the presence of opening influences the strength and failure mode of stiffened plated structures. The main objective of this study is to find the load deflection behaviour, failure mode and strength of stiffened composite plates under inplane and out-of-plane loading. Four glass fiber reinforced stiffened composite plates with and without large opening were fabricated by hand lay-up process using a special lay-up structure to integrate the stiffeners into the flange plate. Initial geometric imperfections in the plate and stiffeners of stiffened composite plates were measured, and tested under inplane and out-of-plane loading. The load deflection behaviour, mode of failure and strength of the tested composite plates were reported. The presence of large opening considerably reduce the strength of stiffened composite plates and no stiffener debonding mode of failure was observed in the tested panels.

Keywords— *Stiffened composite plates, inplane load, out-of-plane load, large opening, failure mode and ultimate strength.*

I. Introduction

Stiffened plates are the primary components in bridge decks, ship structures and offshore oil platforms and subjected to inplane and out-of-plane loading and combination of both loading. Stiffener debonding mode of failure before reaching the ultimate strength was observed in stiffened composite plates fabricated by pultrusion process. The stiffeners have to be integrated in the flange plate to avoid premature debonding mode of failure. Initial geometric imperfections are also formed in the flange plate and stiffeners during the fabrication. Large openings are provided in the deck of ship structures and offshore oil platforms for access and service. The presence of initial geometric imperfections and large opening lead to the complex behaviour of stiffened composite plates under inplane and out-of-plane loading, and the load deflection behaviour, mode of failure and strength are to be evaluated for practical applications.

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The behaviour of stiffened composite plates with different types of stiffeners subjected to various loading was reported by Chiarelli et al. (1996), Romeo and Frulla (1997), Falzon and Steven (1997), Kong et al (1998), Roberts et al (1999), Falzon et al (2000, 2001), Caputo et al. (2002), Ambur et al (2004), Lanzi (2004), Broekel and Prusty (2004), Linde et al (2006), Chen and Soares (2007), Jegley (2007), Orifici et al. (2008), Orifici et al (2008, 2008), Rahima (2009), Boni et al (2012) and Brubak et al (2013). The critical review of literature indicated that the behaviour of stiffened composite plates with large opening that cut the stiffeners, and with initial imperfections has not been studied so far. Based on the review of literature, the main objective of this study was set to fabricate stiffened composite plates with integrated stiffeners and large opening, and to predict the failure mode and ultimate strength under inplane and out-of-plane loading. The scope of work consist of (i) characterization of resin and glass fiber fabric composites, (ii) fabrication of stiffened composite plates with and without large opening, (iii) measurement of initial geometric imperfections in the flange plate and stiffeners, (iv) testing the fabricated panels under inplane and out-of-plane loading and (v) evaluating the failure mode and ultimate strength.

II. Characterization of Materials

Epoxy resin as matrix and glass fiber fabric woven roving mat (WRM) of 610 gsm as reinforcement were selected for the fabrication of stiffened composite plates. The physical and mechanical properties of the epoxy resin and glass fiber reinforced polymer (GFRP) composites were determined by conducting standard tests as per ASTM/ISO/BS/BIS standards. The material properties of epoxy resin and glass fiber fabric composites obtained from the tests are given in Tables 1 and 2.

III. Test Set-up

The test set-up 'A' fabricated by Alagusundaramoorthy et al, (1995) for testing unstiffened and stiffened plates under inplane, out-of-plane and combined loading with a capacity to apply 2000 kN inplane load and capable of testing specimens up to 1000 mm × 1000 mm was used to test stiffened composite plates under inplane and out-of-plane loading (Fig. 1). Inplane load was applied to the test specimens using two hydraulic jacks 'D' of 1500 kN capacity, and the applied load was measured using two load cells 'E' of 1000 kN capacity. The load was applied using a pump 'H' with a distributor 'G'. Load cells were designed and fabricated using AISI SAE 4131 (EN24) steel, and calibrated in the 6000 kN Column Tester available in the Structural Engineering Laboratory. Simply supported boundary conditions were ensured by providing grooved supports 'B' along the

longitudinal and transverse edges. Grooved supports were fabricated by machining the steel flats at the edges and connected to the steel frame. A loading pad 'C' was designed to apply inplane load to the specimen. Out-of-plane-load is applied to the test specimen using inflatable air balloons. Two inflatable air balloons with and without opening were made using neoprene-hypalon fabric. Inflatable air balloon was placed in between the test specimen and grillage and is connected to pneumatic compressor. Rigid grillage attached to the bottom of the test rig act as a support to the inflatable air balloon.

TABLE 1. PROPERTIES OF EPOXY RESIN

Sl. No.	Property	Value
1	Tensile strength	45 MPa
2	Tensile modulus	3589 MPa
3	Failure strain in tension	13433 μ
4	Flexural strength	57 MPa
5	Flexural modulus	3667 MPa
6	Failure strain in flexure	15968 μ
7	Izod Impact strength	4.25 kJ/m ²
8	Barcol hardness	37
9	Peak exothermic temperature	197 °C
10	Gel time	28 minutes
11	Viscosity	7556 centipoises
12	Specific gravity	1.15
13	Water absorption (24 hours)	0.06 %

TABLE 2. PROPERTIES OF GLASS FIBER FABRIC COMPOSITE

Sl. No.	Property	Value
1	Tensile strength in warp (longitudinal) direction	209 MPa
2	Longitudinal modulus (E_1)	15208 MPa
3	Major Poisson's ratio (ν_{12})	0.184
4	Tensile strength in weft (transverse) direction	184 MPa
5	Transverse modulus (E_2)	13523 MPa
6	Minor Poisson's ratio (ν_{21})	0.163
7	Shear strength	50 MPa
8	Shear modulus (G_{12})	4882 MPa
9	Compressive strength	174 MPa
10	Compressive modulus	18974 MPa
11	Flexural strength	313 MPa
12	Flexural modulus	18295 MPa
13	Interlaminar shear strength	24 MPa
14	Lap shear strength	20 MPa
15	Izod impact strength	94 kJ/m ²
16	Water absorption (24 hours)	0.06 %
17	Volume fraction of fibers	0.35
18	Barcol hardness	56

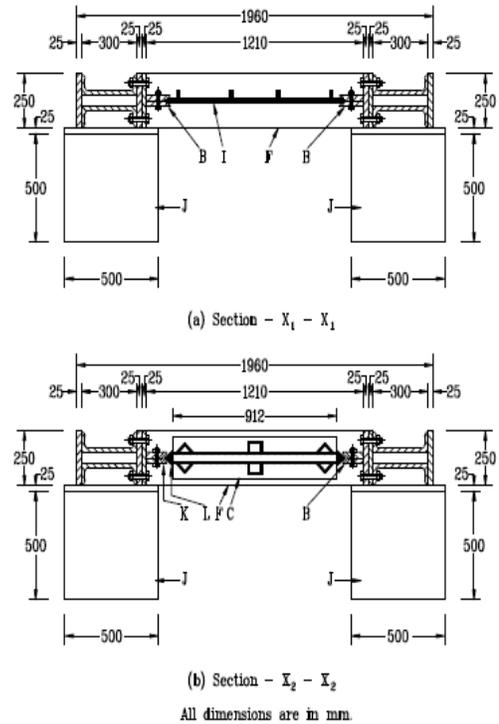
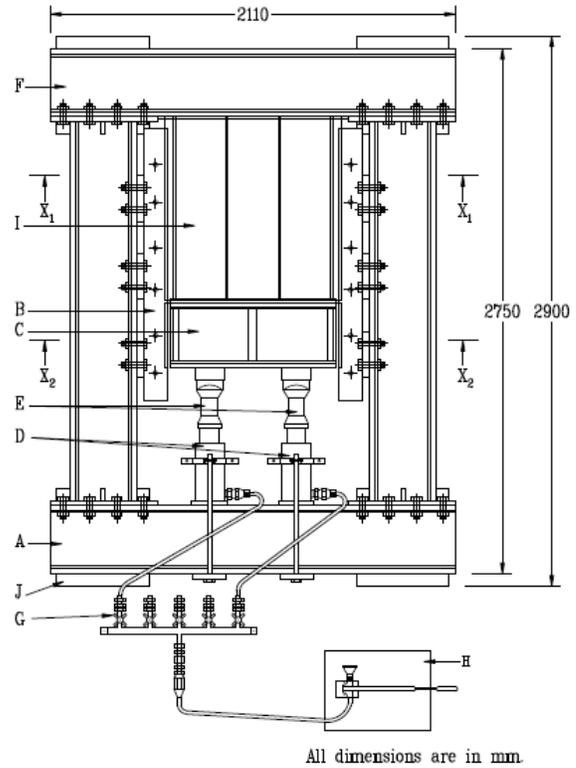


Figure 1. Test set-up

iv. Test Specimens

Aluminium moulds were designed and fabricated in segments for casting stiffened composite plates with and without opening. Flats of 6.35 mm thick were kept in between the segments of the mould to achieve the required thickness of the stiffeners. Glass fiber fabric woven roving mat (WRM) of 610 gsm, epoxy resin LY556 with hardener HY951 were used to fabricate the test specimens. Hand layup process was used for the fabrication. The size of the test specimens ($l \times b$) were 954×954 mm. Eight layers of WRM 610 gsm were used for the flange plate and stiffeners to achieve a thickness of 6.35 mm. A special layup structure was adopted to integrate the stiffeners into the flange plate. The first four layers of WRM passed through the flange plate and stiffeners, and the remaining four layers were bonded on the top of the four layers. Each stiffened composite plate has four flat longitudinal stiffeners. Two stiffened composite plates without opening (GFSCP1 and GFSCP4) and two with large opening that cuts the middle two stiffeners (GFSCPO1 and GFSCPO4) were fabricated. Stiffened composite plates GFSCP1 and GFSCPO1 were tested under inplane loading, and GFSCP4 and GFSCPO4 under out-of-plane loading. Test specimens GFSCP1 and GFSCPO1 are shown in Fig. 2.

v. Initial Geometric Imperfections

Even with very careful control on hand layup process, initial geometric imperfections were formed on the flange plate and stiffeners. The presence of initial geometric imperfections were measured using the fabricated imperfection measurement setup. Grids of size 90 mm x 90 mm were marked on the specimens and placed in the test rig. Dial gauges with magnetic base were fixed to the reference arm of imperfection set-up. The reference arm was moved along the grids, and the initial imperfections at each grid point on the flange plate and stiffeners were measured. Imperfections in the plate were measured at 132 points and 48 points on stiffener. Three dimensional view of the measured initial imperfections were plotted using MATLAB. Plate imperfection (Δ_x), overall imperfection (Δ_{sx}) and torsional imperfection (Δ_{sy}) of stiffeners were calculated from the plots.

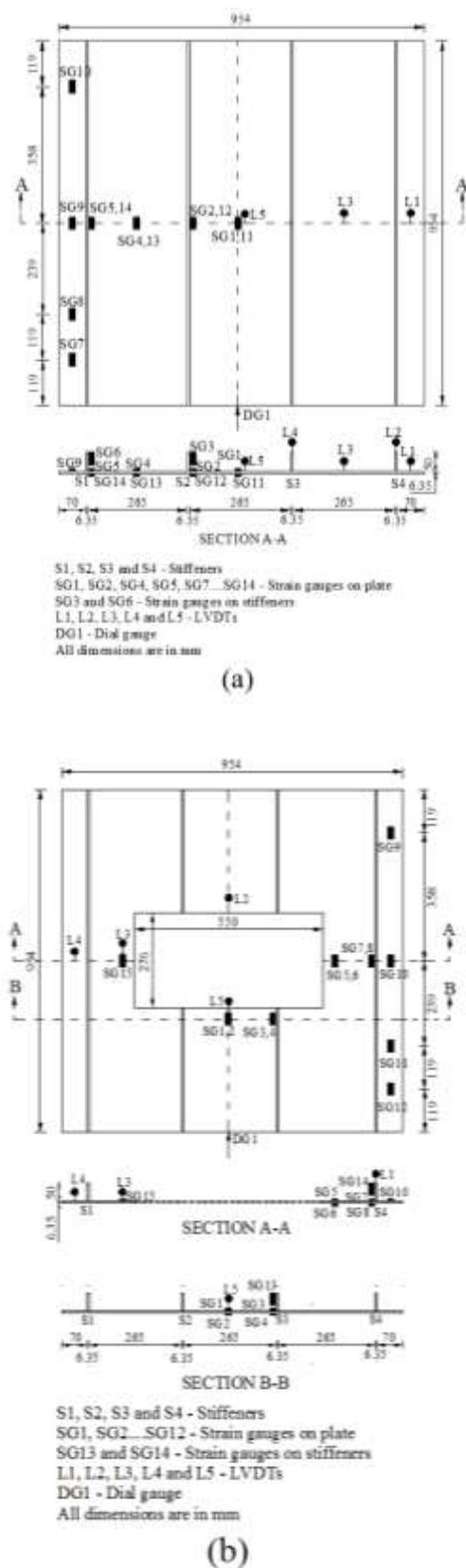


Figure 2. Test specimens GFSCP1 and GFSCPO1

VI. Testing of Stiffened Composite Plates

Stiffened composite plates GFSCP1 and GFSCPO1 were tested under inplane compressive loading and GFSCP4 and GFSCPO4 under out-of-plane loading. Test specimens were instrumented with strain gages, dial gages and LVDTs to measure the strains, axial deformation and out-of-plane deflections. The position of strain gages, LVDTs and dial gauges were shown in Fig. 2. The load cells, strain gauges, LVDTs were connected to a data acquisition system. The inplane and out-of-plane loads were applied gradually and all the readings were recorded at regular intervals. The specimens were loaded upto failure and the failure loads were recorded. The photographs of the test setup, and the tested specimen GFSCP1 are shown in Figs. 3 and 4. The load/axial deformation curves of the specimens GFSCP1 and GFSCPO1 are shown in Fig. 5. The load/out-of-plane deflection curves of specimens GFSCP4 at L5 and GFSCPO4 at L2 are shown in Figs. 6 and 7.



Figure 3. Photograph of the test set-up



Figure 4. Photograph of the tested specimen GFSCP1

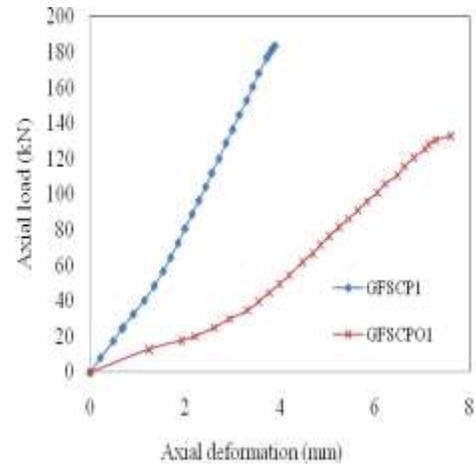


Figure 5. Load/axial deformation curves of GFSCP1 and GFSCPO1

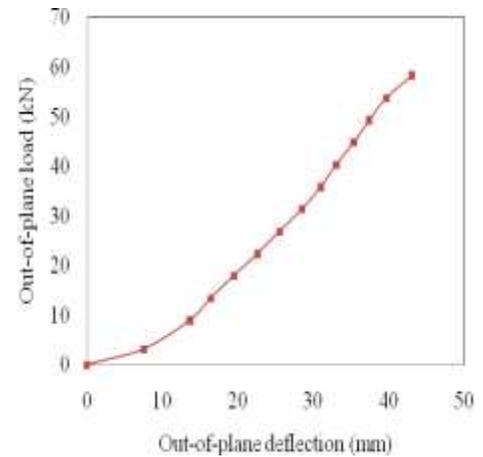


Figure 6. Load/axial deformation curves of GFSCP4 at L5

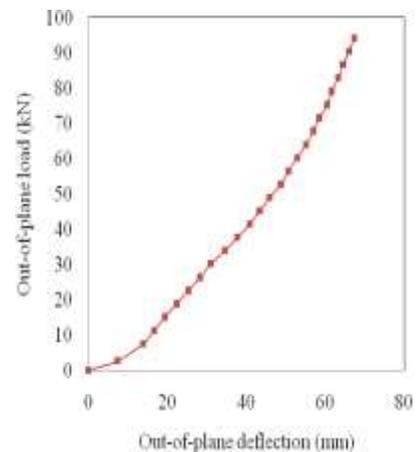


Figure 7. Load/axial deformation curves of GFSCPO4 at L2

VII. Results and Discussions

The ultimate load and maximum axial deformation of GFSCP1 was observed as 184 kN and 3.90 mm. The ultimate

load and maximum axial deformation of GFSCPO1 was observed as 133 kN and 7.60 mm. The specimens GFSCP1 and GFSCPO1 failed by stiffener buckling. The ultimate load and maximum out-of-plane deflection of GFSCP4 was observed as 58 kN and 43 mm, and the specimen failed by stiffener tension. The specimen GFSCPO4 started deflecting continuously without any sign of failure and the loading was stopped at 94 kN, and the out of plane deflection measured at L2 was 67mm. The failure load of the specimen with large opening GFSCPO4 must be lower than GFSCP4. The problem may be in the application of pressure (load) on the specimen GFSCPO4 by the inflatable air balloon. This has to be studied in detail by testing more number of similar specimens.

VIII. Conclusions

The following conclusions are drawn from the tests conducted on stiffened composite plates with and without large opening.

1. Stiffener debonding mode of failure was avoided in all the tested stiffened composite plates by adopting a special lay-up structure in the fabrication.
2. The presence of large opening reduced the ultimate strength by 28% under inplane loading.
3. The stiffened composite plate with large opening did not fail even after applying a pressure greater than the corresponding specimen without opening. Excessive out-of-plane deflection was noticed on the specimen with large opening. The problem may be in the application of pressure on the specimen GFSCPO4 by the inflatable air balloon. This has to be studied in detail by testing more number of similar specimens.

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