Experimental Study on Composite Sandwich Beams with Longitudinal GFRP Webs

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Abstract. This study focused on the bending performance of sandwich beams composed of GFRP skins, PU foam core, and longitudinal GFRP webs. The longitudinal webs were distributed along the length direction of the beam. Six beams were tested to validate the effectiveness of longitudinal webs for increasing the ultimate bending strength. Compared to the control specimen, a maximum of an approximately 316\% and 59\% increase in the ultimate bending strength and bending stiffness can be achieved, respectively. The influences of longitudinal web thickness, fiber paly angle and web spacing on failure mode and bending stiffness were also investigated. Test results demonstrated that the ultimate bending strength and initial bending stiffness can be enhanced by increasing the web thickness and reduce web space. Meanwhile, various failure modes were summarized, including core shear failure, skin compressive failures, and webs buckling failure, due to the presence of the longitudinal webs.

1. Introduction
Sandwich structures composed of two high stiffness skins and a lightweight core, are increasingly used in aerospace, ships, and automobile applications due to their high stiffness and strength-to-weight ratios, good corrosion resistance performance [1–10]. However, very limited attempts have been made to use these materials for structural element applications. The main reason could be that the currently used core materials are foam, woods or foam concrete, which result in the ultimate bearing capacity of the sandwich structure is low and the deformation is large due to their low Young’s modulus.

Extensive experimental and analytical studies on tradition sandwich flexural members with a foam core have been conducted in the past few years. Steeves et al. [11-12] studied the collapse mechanisms of sandwich beams with glass fiber reinforced plastics (GFRP) skins and a foam core. Sharaf et al. [13] studied the flexural behavior of sandwich beams with different polyurethane foam core densities. Umer et al. [14] studied the flexural behavior of VARTM-infused composite sandwich beams with different foam core densities. Tests results suggested that the ultimate bending strength and stiffness of beams were improved with the foam core density and skins thickness increase. But the beam costs and dead loads were also increased. Meanwhile, with the foam core density increase, the sandwich beam finally failed in skin-core delamination failure mode, which limits its ultimate bearing capacity, and the energy dissipation abilities of them were low.
To address this issue, Reis [15] developed a kind of sandwich beams consisted of GFRP skins, PU foam core and through thickness fiber insertions. Reis et al. [16] studied the effects of fiber insertion density, face sheet thickness and panel thickness on the strength and stiffness of the panels. Dawood et al. [17] evaluated the behavior of 3-D GFRP sandwich panels with fiber insertions subject to two-way bending. A corresponding finite element model was also developed to investigate the effects of face sheet thickness, face sheet modulus, fiber insertion density, panel thickness and aspect ratio on the bending strength of the panels. Tests results indicated that the interface delamination can be prevented due to the use of the fiber insertions but the initial bending stiffness was hardly improved.

In this study, a novel composite sandwich beam composed of GFRP skins, a polyurethane (PU) foam core, and GFRP longitudinal webs(GLW beam) was developed (Fig. 1). The GFRP longitudinal webs distributed along the longitudinal direction of beams. The GFRP skins provide major contribution to the bending stiffness while the GFRP longitudinal webs and the PU foam core provides the major of shear stiffness of sandwich structures. This paper presents an experimental study of the flexural behavior of the proposed GLW beams to assess their potential as structural beam elements. Six beams with the same dimensions (1400 × 120 × 80 mm3) were tested under four-point bending to evaluate their ultimate bending strength, failure modes, and bending stiffness.

2. Experimental program

2.1. Description of test specimens and parameters

In this study, six beams were manufactured and tested. All beams had the same width (b) and length (l), which were 120 and 1400 mm, respectively. A control panel, namely, specimen GLW-CON. The other beams were manufactured with a GFRP longitudinal web with varying thickness of the web (tw), spacing of the web (s), and the fiber play angle (θ) of the webs. The details of beams are summarized in Table 1.

| Specimen NO. | Illustration | L (mm) | B (mm) | H (mm) | Weight (kg) | Longitudinal webs (mm) | Core density |
|--------------|--------------|--------|--------|--------|-------------|------------------------|-------------|
| GLW-CON1     |              | 1200   | 120    | 80     | 4.58        | --                     | 150         |
| GLW-1-2-90   |              | 1200   | 120    | 80     | 4.83        | 1.2                    | 120 [0/90]  |
| GLW-2-2-90   |              | 1200   | 120    | 80     | 5.10        | 1.2                    | 60 [0/90]   |
| GLW-2-4-90   |              | 1200   | 120    | 80     | 5.70        | 2.4                    | 60 [0/90]   |
| GLW-2-4-60   |              | 1200   | 120    | 80     | 5.73        | 2.4                    | 60 [±60]    |
| GLW-2-4-45   |              | 1200   | 120    | 80     | 5.80        | 2.4                    | 60 [±45]    |

1*GFM-a-b: a means the number of the horizontal GFRP layers; b means the kinds number of the PU foam core.
2.2. Material properties
GFRP skins and longitudinal webs composed of [0/90°] symmetric E-glass woven fiber (800 g/m²) and HS-2101-G60 unsaturated polyester resin. The average thickness of the cured GFRP laminate is 4.8 mm. The densities of the PU foam core is 150 kg/m³. The test specimen for the skin is manufactured by the VARTM process.

2.3. Test set-up and instrumentation
Four-point bending configuration tests were carried out on each specimen according to ASTM C393 [18]. The clear span (L) between the two roller supports was 1200 mm. Beams were loaded to failure using a 980 kN MTS hydraulic universal testing machine (with a precision of 0.22 N) at a displacement rate of 2 mm/min. To measure the deflections of the beam, three linear variable displacement transducers (LVDTs) with a stroke of 100 mm, installed at middle span and support locations. Six electric resistance strain gauges, pasted on the top and bottom skins, were adopted in the four-point bending tests.

3. Experimental results and discussion

3.1. Experimental results

3.1.1. Failure mode
The macroscopic failure modes of specimens can be categorized as three primary types: (1) core shear failure, which occurred in control specimen (Fig. 2a); (2) webs shear buckling failure, which occurred in control specimens GLW-1-2-90 and GLW-2-2-90 (Fig. 2b); (3) top skin compressive failure (Fig. 2c), which is common in specimens with a higher webs value ratios (GLW-2-4-90, GLW-2-4-60, and GLW-2-4-45). The microscopic phenomena that result in the corresponding macroscopic failure modes can be described, respectively, as follows: (1) the maximum shear strain of the core exceeds its ultimate shear strain. (2) The shear stress of the webs exceeds the critical shear buckling stress, the webs failed in buckling failure mode. (3) the webs thicknesses of Specimens GLW-2-4-90, GLW-2-4-60, and GLW-2-4-4 is 2.4 mm, which had larger bending and shear stiffness and critical buckling stresses than those of specimens with 1.2 mm and 1.6 mm thicknesses, respectively. Hence, the critical buckling stress of the webs was larger than its yield stress, when the compressive strain of the top skin reaches its ultimate strain, the compressive failure occurred.

![Figure 2. Failure modes of composite GLW beams. (a) GLW-CON; (b) GLW-1-2-90; (c) GLW-2-4-90.](image)

3.1.2. Load-deflection behaviour
The load-deflection behaviour of individual GLW beams under four-point static bending is shown in Figs. 3. The deflection of specimen GLW-CON increased almost linearly with load up to final failure. The specimen failed at an applied load of 10.8 kN with a deflection of 22 mm. The load of specimen GLW-1-2-90 increased almost linearly with deflection but showed a reduction in stiffness at an applied load of 10 kN. The beam failed at an applied load of 15.6 kN with a deflection of 31.1 mm due to shear buckling of the webs. A similar load-deflection behavior was observed in specimen GLW-2-2-90, which failed at an applied load of 19.9 kN with a deflection of 32.3
mm. The load dropped by 27% after failure. The deflection of specimen GLW-2-4-90 increased almost linearly with load up to final failure with a load of 42.4 kN. When the maximum load was reached, an abrupt drop in the load was observed and the specimens failed subsequently with the top skin failure of compressive failure. The similar load-deflection behavior was observed in specimens GLW-2-4-60, and GLW-2-4-45. The values of the load and deflection of the specimens were shown in Table 2.

Figure 3. Load-deflection behavior of GLW beams.

3.1.3. Load-strain behaviour. The load strain behavior of the top and bottom GFRP skins in the longitudinal direction at mid-span were shown in Fig. 4. Test results suggested that the strains in both tension and compression increased linearly with load at the early stage of load application for all the tested specimens. The measured maximum tensile strain was 0.99% (specimen GLW-2-4-60), lower than the values obtained during material tests (1.84%). The measured maximum compressive strain was about 0.89% (specimens GLW-2-4-90, GLW-2-4-90, and GLW-2-4-90), which is a bit larger than the values of which the fiber composite skins failed in compression determined from the coupon tests (0.82%).
3.2. Parameter study

3.2.1. Influence on web volume ratio. Fig. 3(a) shows the effect of web thickness ($t_w$) on the load-deflection behavior of beams. Using thicker web ($t_w = 2.4$ mm for Specimens GLW-2-4-90) for strengthening the beams increased the ultimate bending strengths (as compared to Specimens GLW-2-2-90). Because increasing the web thickness can result in a larger ratio of the volume of web to foam core, which can increase the equivalent Young’s modulus, a larger ultimate bending strength can also be achieved. Fig. 3(b) shows the effect of web spacing ($s$) on the $P_u$ of beams. In Fig. (b), the $P_u$ of Specimen GLW-2-2-90 ($s = 60$ mm) was 24.1 kN, which was 32% and 123% greater than those of Specimens GLW-2-2-90 ($s=120$ mm) and GLW-CON, respectively. As same as the thickness of the webs, decreasing web spacing can increase the ratio of the volume of web to foam. Hence, the equivalent Young’s modulus can be improved. Furthermore, the larger ratio of the volume of web to foam can enhance the shear capacity and skin/core adhesive strength of beams. Therefore, smaller web spacing leads to a higher ultimate bending strength. Table 2 lists the calculated bending stiffness $EI$ and the stiffness-to-weight ratio. The bending stiffness $EI$ of specimen GLW-2-4-90 was 24%, 55% and 106% larger than those of specimens GLW-2-2-90, GLW-1-2-90, and GLW-CON, respectively, which indicated that the bending stiffness increase with the volume of the webs increase.
Table 2. Summary of the stiffness, and strain of GLW beams.

| Specimen       | Weight (kg) | ΔP/Δδ (N/mm) | EIex ($\times 10^{10}$ N mm$^2$) | EIpre ($\times 10^{10}$ N mm$^2$) | EIex/EIpre | EIex/W $^1$ | Maximum strain (mm/mm) | Tensile (%) | Compressive (%) |
|----------------|-------------|--------------|---------------------------------|----------------------------------|------------|--------------|------------------------|-------------|-----------------|
| GLW-CON        | 4.58        | 607          | 2.00                            | 2.85                             | 1.43       | 0.44         | 2140                   | 2140        | 1914            |
| GLW-1-2-90     | 4.83        | 806          | 2.65                            | 3.29                             | 1.24       | 0.55         | 3234                   | 3234        | 3100            |
| GLW-2-2-90     | 5.1         | 1008         | 3.32                            | 3.52                             | 1.06       | 0.65         | 3465                   | 3465        | 3249            |
| GLW-2-4-90     | 5.7         | 1250         | 4.11                            | 4.45                             | 1.08       | 0.72         | 8695                   | 8695        | 8460            |
| GLW-2-4-60     | 5.73        | 1288         | 4.24                            | 4.52                             | 1.07       | 0.74         | 9860                   | 9860        | 8890            |
| GLW-2-4-45     | 5.8         | 1314         | 4.32                            | 4.46                             | 1.03       | 0.75         | 8640                   | 8640        | 8353            |

$^1$EIex/W: Strength-to-weight ratio.

3.2.2. Influence on web fiber play angle. Fig. 3(c) shows the effect of fiber play angle ($\theta$) of the webs on the load-deflection behavior of beams. The stiffness of specimen GLW-2-4-45 ($\theta = \pm 45$) is 316% greater than that of Specimens GLW-CON, and about 7% greater than that of Specimens GLW-2-4-90 ($\theta = 0/90$) and GLW-2-4-60 ($\theta = \pm 60$). The beam with composite foam core showed a more ductile failure mode. The bending stiffness $E_{Iex}$ for specimen GLW-2-4-45 was 2% and 5% larger than those of specimens GLW-2-4-60 and GLW-2-4-90, respectively. And the results indicated that the fiber play angle have little influence on the bending stiffness and strength. Additionally, specimen GLW-2-4-45 shows the highest stiffness-to-weight ratio, which was 3% and 71% larger than those of specimens GLW-2-4-90 and GLW-CON, respectively.

4. Conclusion

This paper presents an experimental study on sandwich beams with GFRP skins, PU foam core, and longitudinal GFRP webs loaded in four-point bending. The main findings are summarized as follows:

1. The experimental results show that compared to the normal sandwich beam with a foam core, a maximum of an approximately 316% increase in the ultimate bending strength of beams can be achieved due to the presence of longitudinal GFRP webs.

2. The thicker GFRP webs and the smaller web space, the greater the ultimate bending strength and initial bending stiffness of composite beams.

3. This new type of sandwich beams is still under development; the corresponding unified design procedure will be proposed to aid structural engineers in designing this new type of beams, and the minimum weight design procedure will also be provided.

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