Research Article

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The energy absorption behavior of novel composite sandwich structures reinforced with trapezoidal latticed webs

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Abstract: This article proposed an innovative composite sandwich structure reinforced with trapezoidal latticed webs with angles of 45°, 60° and 75°. Four specimens were conducted according to quasi-static compression methods to investigate the compressive behavior of the novel composite structures. The experimental results indicated that the specimen with 45° trapezoidal latticed webs showed the most excellent energy absorption ability, which was about 2.5 times of the structures with vertical latticed webs. Compared to the traditional composite sandwich structure, the elastic displacement and ultimate load-bearing capacity of the specimen with 45° trapezoidal latticed webs were increased by 624.1 and 439.8%, respectively. Numerical analysis of the composite sandwich structures was carried out by using a nonlinear explicit finite element (FE) software ANSYS/LS-DYNA. The influence of the thickness of face sheets, lattice webs and foam density on the elastic ultimate load-bearing capacity, the elastic displacement and initial stiffness was analyzed. This innovative composite bumper device for bridge pier protection against ship collision was simulated to verify its performance. The results showed that the peak impact force of the composite anti-collision device with 45° trapezoidal latticed webs would be reduced by 17.3%, and the time duration will be prolonged by about 31.1%.

Keywords: composite sandwich structure, trapezoidal latticed webs, energy absorption, FE modeling

1 Introduction

The transportation industry is developing rapidly, and the amount, capacity and velocity of ships are improving constantly; however, the ship–bridge collision events are happening frequently [1–3]. Extensive research about energy buffering and absorption materials and structures has been conducted to develop anti-collision devices [4–7]. Some kinds of anti-collision devices have been successfully developed according to the principle of energy absorption and momentum buffering [8–10]. The commonly used anti-collision protection device for bridge piers in China is the framed steel fender system, which exhibited the shortcomings of bad corrosion resistance and high maintenance cost [11,12]. Moreover, the framed steel fender system was also difficult to be used in some lightweight engineering structures for its low specific strength.

Composite sandwich structures have received great attention by virtue of the high specific strength and specific stiffness, excellent corrosion resistance, nice energy absorption behavior and strong designability [13–23]. The traditional lattice-web reinforced composite sandwich structures as anti-collision devices had been applied to several bridges (Figure 1). Nevertheless, the initial stiffness and ultimate strength were relatively low, and the serious interface stripping phenomenon also appeared in the test results. Wu et al. [24] proposed a novel foam-filled glass-fiber reinforced polymer (GFRP) tubes and validated the high compressive capacity and efficient energy-absorbing capacity. Wang et al. [25] invented the lattice web reinforced composite foam sandwich structure and found that when the lattice web was subjected to shear stress and compressive stress, it could restrain stripping of the surface layer and the core material simultaneously. However, further investigations discovered that the traditional lattice web reinforced foam sandwich structure had two dominating defects, i.e., the huge peak crushing force and the sharp tremendous bearing load decline [Figure 10(a)].

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Figure 1: Application of the orthogonal lattice web reinforced composite sandwich panels as anti-collision devices: (a) Guang Zhou to Shen Zhen AloneRiver Expressway Bridge, (b) Xin Meng Ge Bridge, (c) Huang Gang Yangtze River Bridge.

Therefore, this article proposes the foam-filled composite sandwich structures reinforced by trapezoidal latticed web through changing the space position of the latticed web. The failure mode of the composite structures reinforced by the trapezoidal latticed web can be improved to prevent the sudden decrease of the bearing load and to extend the elastic stroke of the bearing capacity; meanwhile, the energy absorption characteristics can be enhanced.

2 Materials and manufacturing

2.1 Specimen description

Four types of foam-filled composite structures were manufactured using the vacuum-assisted resin infusion process (VARIP) in Advanced Engineering Composites Research Center of Nanjing Tech University. These structures were composed of GFRP face sheets and foam cells wrapped by GFRP trapezoidal lattice webs. The face sheets and webs were made of bi-axial [0/90] glass fiber laminates ($800 \text{ g}\cdot\text{m}^{-2}$) and unsaturated polyester resin. The bi-axial [-45/45] glass fiber laminates ($800 \text{ g}\cdot\text{m}^{-2}$) were used to wrap the PU foam ($40 \text{ g}\cdot\text{m}^{-3}$) cells. All structures were 300 mm in length, 300 mm in width and 150 mm in height. The thicknesses of face sheets (t_s) and webs (t_w) were 2.4 mm (t_s). The control specimen TS-V was reinforced with GFRP vertical lattice cells. The specimen TS-V was used to make an investigation of normal composite structures' energy absorption behavior. Specimens TS-T-A45, TS-T-A60 and TS-T-A75, which were formed with GFRP trapezoidal webs, were used to investigate the influence of web angle on the energy absorption behavior of a novel composite sandwich structure. Figure 2 shows the outline of the novel composite sandwich structures reinforced by GFRP trapezoidal

latticed webs. The detailed information of each specimen is listed in Table 1.

2.2 Manufacturing procedures

VARIP was used to manufacture the specimens, and the fabricating procedures can be divided into five operating sequences [21]: (a) cutting foam core, (b) wrapping foam core, (c) resin infusion, (d) curing the resin and (e) cutting components according to the dimensions. The detailed manufacturing procedures could be found in reference [21].

2.3 Material properties

Tensile tests of GFRP sheets [Figure 3(b)] were conducted on five rectangular laminate samples [Figure 3(a)] with a size of $250 \times 25 \times 2.4 \text{ mm}^3$ based on ASTM D3039/D3039M-14 [26]. The medial tensile strength is 208.1 MPa (the standard deviation is ± 3.11), and the medial modulus is 19.1 GPa (the standard deviation is ± 0.48), which fluctuates

Figure 2: The novel foam-filled sandwich composite panels reinforced by GFRP trapezoidal latticed web.

Table 1: Dimension parameter of specimens

Specimen	Illustration	L (mm)	W (mm)	H (mm)	t_s (mm)	t_w (mm)	Angle ($^\circ$)	m (kg)
TS-V		300	300	150	2.4	2.4	—	2.38
TS-T-A45		300	300	150	2.4	2.4	45	4.95
TS-T-A60		300	300	150	2.4	2.4	60	4.90
TS-T-A75		300	300	150	2.4	2.4	75	5.28

between 18.4 and 19.5 GPa. Simultaneously, the compression properties of the five cubic GFRP laminate samples with a size of $10 \times 10 \times 30 \text{ mm}^3$ were evaluated using compression tests [Figure 3(c)] according to ASTM D695-10 [27]. The medial compressive strength is 84.7 MPa (the standard deviation is ± 2.48), and the medial compressive modulus is 5.0 GPa (the standard deviation is ± 0.52), which fluctuates between 4.5 and 5.6 GPa. Table 2 presents the corresponding results.

Five PU foam samples with a size of $50 \times 50 \times 50 \text{ mm}^3$ were used to evaluate the mechanical properties in accordance with ASTM C365/C365M-16 [28]. The displacement rate of all compression tests were $2 \text{ mm} \cdot \text{min}^{-1}$. Figure 3(d) shows the compression test of PU foam, and the resulting properties of the PU foam are listed in Table 3.

3 Experimentation

3.1 Experimental set-up

Figure 4 shows the experimental setup. The universal testing machine with a static capacity of 200 kN was used to conduct the quasi-static compression tests. Each specimen

was placed between two rigid plates, and the bottom rigid plate was fixed on the base of the test device. A constant loading rate of $2 \text{ mm} \cdot \text{min}^{-1}$ of the movable top plate was applied to compress the specimens.

3.2 Failure modes

The test loading process of TS-V specimen is shown in Figure 5, where the specimen is compressed to 70% of its original height (105 mm). The bearing capacity of the TS-V increases linearly to 116.1 kN at the beginning of loading [Figure 10(a)]. When the compression displacement increased from 5.4 to 8.2 mm, the left-side lattice was bent and stripped of foam with a clear sound. The right vertical lattice was bent, and the foam was completely peeled off with the creak of the specimen, which formed the penetrating crack, and the outer foam was torn and bulging out. The bearing capacity of the specimen rapidly decreased by 43.9 kN. With the increase of compression displacement, the specimen was compacted gradually, and the bearing capacity was stable after a short decrease. When the compression displacement reaches 49.1 mm, the vertical lattice structure was compressed gradually, and the bearing capacity of the

Figure 3: Material properties test: (a) GFRP sheets: five tension coupons; (b) tension test of GFRP sheets; (c) compression test of GFRP sheets; and (d) compression test of PU foam.

Table 2: Material properties of face sheets

Components	Properties	Face sheets
Compression	Yield strength (MPa)	84.7 ± 2.48
	Young's modulus (GPa)	5.0 ± 0.52
Tension	Yield strength (MPa)	208.1 ± 3.11
	Young's modulus (GPa)	19.1 ± 0.48

Table 3: Material properties of foam

Components	Properties	PU foam
Compression	Yield strength (MPa)	0.14 ± 0.03
	Young's modulus (GPa)	2.27 ± 0.40

Figure 4: Quasi-static experiment on foam sandwich composite with spatial reinforced lattice webs.

specimen fluctuated. Finally, the specimen was compacted and the bearing capacity increased steadily.

The test loading process of TS-T-A45 specimen is shown in Figure 6. When the compression displacement increased to 33.7 mm, the horizontal lattice slowly flexed, the angle between the diagonal lattice and the horizontal lattice gradually decreased, the specimen was extruded inward on both sides, and the bearing capacity continued to increase linearly until 63.7 kN. Subsequently, the lower lattice was gradually separated from the upper lattice, and the bearing capacity was slightly fluctuated. With the increase of the compression displacement, the bending deformation of the horizontal lattice increased gradually, the oblique lattice was pressed to the horizontal lattice, the foam in the trapezoidal lattice was compacted gradually, and the bearing capacity of the specimen continuously improved.

The test loading process of TS-T-A60 specimen is shown in Figure 7. During the loading process, the trapezoidal horizontal lattices continued to bend, and the trapezoidal lattices of the upper and lower layers approached each other gradually under compression without obvious brittle failure. The two sides of the specimen were extruded inward, and the foam and lattice structures on both sides were broken off. At the later stage of loading, a small amount of oblique latticework was compressed and bent without obvious brittle fracture. The bearing capacity of the specimen increased continuously during the whole compression process, and only a small amount of gentle stage appeared.

The test loading process of TS-T-A75 specimen is shown in Figure 8. At the beginning of the loading process, the bearing capacity of the specimen increased

Figure 5: Quasi-static experiment of TS-T-V: (a) beginning, (b) $\Delta = 15$ mm, (c) $\Delta = 30$ mm, (d) $\Delta = 45$ mm, (e) $\Delta = 60$ mm, (f) $\Delta = 75$ mm, (g) $\Delta = 90$ mm and (h) $\Delta = 105$ mm. (Note: Δ represents the compression displacement).

Figure 6: Quasi-static experiment of TS-T-A45: (a) beginning, (b) $\Delta = 15$ mm, (c) $\Delta = 30$ mm, (d) $\Delta = 45$ mm, (e) $\Delta = 60$ mm, (f) $\Delta = 75$ mm, (g) $\Delta = 90$ mm, (h) $\Delta = 105$ mm.

linearly to 56.6 kN when the compression displacement is increased to 5.7 mm. When the compression displacement was up to 15 mm, the horizontal lattice was gradually bent and deformed, and the displacement of the upper and lower trapezoidal lattice was shifted. With the compression process, the upper right, the lower left and middle trapezoidal oblique lattice delaminated, and the bearing capacity fluctuated up and down. In the end, the bearing capacity increased continuously during the compaction stage.

From all the test results, three main macro-failure modes can be summarized: (1) local buckling of longitudinal lattice [Figure 9(a)], which occurs in TS-V specimens; (2) the interface delamination of lattice is common in TS-T-A75 specimens [Figure 9(b)]; and (3) bending deformation of lattice [Figure 9(c)], which is more common in TS-T-A45, TS-T-A60 specimens. The mechanism analysis of the aforementioned failure modes are as follows: (1) before reaching the ultimate compressive strength, the compressive

stress of the longitudinal lattice web reaches the critical buckling stress; (2) the interface tensile stress is greater than the bond strength of lattice web and foam core; (3) virtue of the angle of TS-T-A45 and TS-T-A60 is relatively small, the oblique lattices are relatively long, the deformation of different trapezoidal lattices is coordinated during compression deformation, and the delamination of lattices is not produced, and then the failure of the specimen shows good integrity.

3.3 Load–displacement behavior

The load–displacement curves of the test specimens are illustrated in Figure 10, and the loads and displacements at the load positions are noted. The elastic ultimate bearing capacity (the P_E) of TS-V is 116.1 kN, while the elastic displacement is only 5.4 mm, and the initial stiffness (K) is 21.5 kN·mm⁻¹. Then, the bearing load suddenly

Figure 7: Quasi-static experiment of TS-T-A60: (a) beginning, (b) $\Delta = 15$ mm, (c) $\Delta = 30$ mm, (d) $\Delta = 45$ mm, (e) $\Delta = 60$ mm, (f) $\Delta = 75$ mm, (g) $\Delta = 90$ mm, (h) $\Delta = 105$ mm.

Figure 8: Quasi-static experiment of TS-T-A75: (a) beginning, (b) $\Delta = 15$ mm, (c) $\Delta = 30$ mm, (d) $\Delta = 45$ mm, (e) $\Delta = 60$ mm, (f) $\Delta = 75$ mm, (g) $\Delta = 90$ mm, (h) $\Delta = 105$ mm.

decreased to 92.56 kN on account of local buckling of the longitudinal lattice. The bearing capacity after the compression stroke (the P_S) is only 38.36 kN [Figure 10(a)]. This huge reduction in bearing capacity in a short time is not beneficial to energy absorption and may cause secondary damage [21]. The elastic ultimate capacity of TS-T-A45 specimen is 66.7 kN, but the elastic displacement is 33.7 mm. The load-carrying capacity rose sharply after a small fluctuation, and P_S increased significantly to 168.70 kN after the compression stroke. The curves of TS-T-A60 and TS-T-A75 are similar to that of TS-T-A45, but the elastic displacement of TS-T-A60 and TS-T-A75 is shortened to 16.4 and 7.5 mm, respectively. Table 4 lists the main testing results.

3.4 Total absorbed energy (E_a)

E_a is the energy absorbed by the specimen when the compression stroke is 70% of the specimen height. The energy absorption value, which is the area surrounded by

the curve of load–displacement and the abscissa axis (displacement), is a main index to assess the energy absorption performance. E_a is expressed as equation (1)

$$E_a = \int_0^S F(s) ds \quad (1)$$

where S is the compression displacement.

As the compression stroke increases, the energy absorption values of each stage are listed in Table 5. The energy absorption value is primarily affected by the initial stiffness of the specimen at the early stage of loading. When the compression ratio reaches 0.1, the energy absorption value of the TS-V specimen is larger than that of other cross-section specimen for its high initial stiffness. When the compression ratio increases gradually, the vertical lattice web of the TS-V specimen has completely buckled, and its bearing capacity fluctuates in a small range. The energy absorbed by the TS-V specimen increases linearly with the increase of the compression ratio, but the energy absorption value is the smallest, with a total absorption of 3,060 J.

Figure 9: Failure modes of specimens: (a) local buckling, (b) interface delamination, (c) bending deformation of lattice.

Table 4: Mean experimental results

Specimen	P_E (kN)	ΔP_1 (mm)	K (kN·mm ⁻¹)	P_S (kN)	E_a (J) 0.7	E_S (J·kg ⁻¹)	F_m (kN)	Failure mode
TS-V	116.1	5.4	21.5	38.36	3,060	1285.7	29.1	Local bucking
TS-T-A45	66.7	33.7	2.0	168.70	7,326	1373.1	64.7	Bending deformation of lattice
TS-T-A60	36.9	16.4	2.3	129.39	6,431	1312.5	61.2	Bending deformation of lattice
TS-T-A75	63.3	7.5	8.4	144.65	7,671	1452.8	73.1	Interface delamination

The load–displacement curve of TS-T-A45 and TS-T-A60 shows a stable increasing trend, and the bearing capacity increases as the compression displacement increasing. Therefore, the trend of energy absorption of the two forms is similar, the energy absorption value increases steadily in the middle period and then increases rapidly during the later stage of loading. The load–displacement curve of TS-T-A75 specimen fluctuated greatly in the middle period of loading, but its energy absorption value is the biggest (7,671 J) due to more lattice failure. The energy absorption of TS-T-A45 (7,326 J), TS-T-A60 (6,431 J) and TS-T-A75 is 2.4, 2.1 and 2.5 times that of TS-V, respectively.

3.5 Specific energy absorption (E_S)

E_S is another main index to estimate the energy absorption property of the specimen. Equation (2) expresses E_S as follows:

$$E_S = \frac{E_a}{m} \quad (2)$$

where m is the specimen mass (compared with Table 1).

E_S capacities of the four representative specimens are presented in Table 4. Among these specimens, TS-V had the smallest E_S capacity of 1285.7 J·kg⁻¹, while TS-T-A75 had the greatest E_S capacity of 1452.8 J·kg⁻¹.

3.6 Mean crushing load (F_m)

F_m is the average bearing capacity of the specimen in the whole process of quasi-static compression, which is one of the important parameters to quantify the crushing process of the specimen. F_m is defined in equation (3).

$$F_m = \frac{E_a}{S} \quad (3)$$

where S is the total compression displacement of each specimen, and S is equal to 105.

F_m values are presented in Table 4. The average crushing force of the TS-V specimen is the smallest with the value of 29.1 kN, while the average crushing force of TS-T-A75 specimen is the largest and the difference between them is 48.5 kN. The average crushing forces of TS-T-A45 and TS-T-A60 are 64.7 and 61.2 kN, respectively. Among these four proposed specimens, the average crushing force of three kinds of trapezoidal latticed webs (TS-T-A45, TS-T-A60 and TS-T-A75) is much higher than that of vertical latticed webs (TS-V), which would be helpful for stopping specimens TS-T-A45, TS-T-A60 and TS-T-A75 from collapsing at the initial impact process when used as a material of the bumper system to protect the bridge from ship collision.

4 Finite element modeling

4.1 Modeling details

The composite structures were modeled and simulated by using the finite element software ANSYS/LS-DYNA. The geometric model was composed of two rigid plates and the composite structure in between. The size of the model depends on the design size of the specimen. Bond slip between GFRP surface, latticed web and polyurethane foam is not considered. Hexahedral Mesh was used to mesh the polyurethane foam of the vertical lattice model, and tetrahedral mesh (free mesh) was used to mesh the

Table 5: Energy absorption of tested specimens (J)

	0.1	0.2	0.3	0.4	0.5	0.6	0.7
TS-V	710	1,073	1,444	1,927	2,295	2,623	3,060
TS-T-A45	253	962	1,865	2,835	4,046	5,428	7,326
TS-T-A60	306	923	1,658	2,510	3,552	4,800	6,431
TS-T-A75	725	1,667	2,697	3,628	4,671	5,989	7,671

Note: Δ represents the compression ratio of the specimen.

Figure 10: Load–displacement curves of specimens with spatial webs: (a) TS-V, (b) TS-T-A45, (c) TS-T-A60, (d) TS-T-A75.

polyurethane foam of the oblique lattice model, and the grid is divided as shown in Figure 11.

is used to simulate the foam, test loading rigid plate and backing rigid plate.

4.1.1 Element type

In this article, SHELL163 element [29] is used to simulate the inner and outer surfaces, and vertical and inclined webs of GFRP specimens with different cross sections when the space lattice reinforced foam sandwich composite is simulated. The thickness of different GFRPs is defined by setting real constant, and SOLID164 element

4.1.2 Material mode

The GFRP face sheets and lattice webs are simulated using the composite damage model (material number 22). The FE model material parameters are mainly presented in Table 6. The composite orthotropic material with optional brittle failure can be defined according to the advice of Chang and Chang [30,31]. The crushable

Figure 11: Geometric model and mesh mode of TS-T-A45: (a) geometric model and (b) mesh mode.

foam model (material type 63) with a failure criterion was applied to simulate the PU foam. The top and bottom rigid plates were simplified as rigid plates simulated by *MAT_RIGID.

4.1.3 Loading and boundary conditions

The FE model boundary control condition is consistent with the experimental loading control condition. The bottom rigid plate was fixed, and the loading plate is loaded by the method of specifying loads, and the loading speed is controlled to be $2 \text{ mm} \cdot \text{min}^{-1}$.

4.1.4 Contact definition

In the FE modeling of composites, the interface slip and contact between different elements are crucial problems, particularly the problem related to the composite deformation [3]. The contact algorithm *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE was used between the loading plate and the composite specimen, and the static and dynamic friction coefficients were set to 0.1 [32].

4.2 Numerical simulation verification

Figure 12 shows the deformation diagram of the TS-V specimen obtained by finite element numerical simulation coincides with the experimental compression deformation results. The bending failure of TS-V specimens

with vertical lattice web is the same as the experimental result. The polyurethane foam was compressed gradually, and the shear failure of the outer foam did not occur, which was consistent with the experimental phenomenon.

Figures 13–15 show the strain and stress of trapezoid specimens. The horizontal lattice structure of 45° and 60° trapezoid specimens is gradually bent, the oblique lattice structure is gradually compressed and close to each other, and the foam is compressed and compacted, which agrees well with the experimental phenomena. The horizontal lattice of 75° trapezoidal lattice is gradually bent in FEM numerical simulation, which is different from the failure phenomenon of the delamination of the diagonal lattice during the compressed process.

Figure 16 draws load–displacement curves of numerical simulations and experimental data. In the stage of elastic compression, the finite element simulation value is very close to the experimental curve. In the compaction stage, the failure element is deleted when the compressive stress is too large or the shear failure is reached because of the failure criterion of the crushing foam model (*MAT_Crushable_Foam) is added in the finite element simulation. Therefore, the finite element simulation curve is slightly lower than the test loading curve, and the bearing capacity does not show an obvious strengthening rising stage.

The comparison of the elastic ultimate load, elastic deformation and initial stiffness between the numerical simulations and results is presented in Table 7. The numerical result of the initial stiffness of the specimen is slightly larger than the experimental result. First, the error is caused by the inevitable convex fold at the outer boundary of the lattice web, which is completely

Table 6: The parameters of GFRP

Property	LS-DYNA parameter	Experimental value
Density	R_O	$1.8 \text{ g} \cdot \text{cm}^{-3}$
Modulus in longitudinal direction	E_A	19.1 GPa
Modulus in transverse direction	E_B	19.1 GPa
Modulus in C direction	E_C	4.98 GPa
Shear modulus	G_{AB}	2.5 GPa
Shear modulus	G_{AC}	1.25 GPa
Shear modulus	G_{BC}	1.25 GPa
Poisson's ratio	PRBA	0.15
Longitudinal tensile strength	XT	208.1 MPa
Transverse tensile strength	YT	208.1 MPa
Compressive strength in longitudinal direction	XC	84.7 MPa
Compressive strength in transverse direction	YC	84.7 MPa
Nonlinear shear coefficient	α	0.3
Shear strength	SC	55 MPa

Figure 12: Strain and stress of specimen TS-V: (a) GFRP, (b) PU foam, (c) quasi-static experiment.

Figure 13: Strain and stress of specimen TS-T-A45: (a) GFRP, (b) PU foam, (c) quasi-static experiment.

Figure 14: Strain and stress of specimen TS-T-A60: (a) GFRP, (b) PU foam, (c) quasi-static experiment.

Figure 15: Strain and stress of specimen TS-T-A75: (a) GFRP, (b) PU foam, (c) quasi-static experiment.

compressed at the beginning of the test compression leading to the lower initial stiffness and bearing capacity. Second, when the trapezoid lattice web is formed in one-step vacuum injection molding, the sandwich foam wrapped

with fiber will slide along the inclined side when it is pressed from both sides; as a result, there are inevitable errors between the established finite element model and the actual machined specimen. The debonding failure of lattice web

Figure 16: Comparison of load–displacement curves between the numerical simulations and results: (a) vertical lattice webs, (b) 45° trapezoid space lattice webs, (c) 60° trapezoid space lattice webs, (d) 75° trapezoid space lattice webs.

Table 7: Comparison of the elastic ultimate load and initial stiffness between the numerical simulations and results

Specimen	P_E (kN)			ΔP_1 (mm)			K (kN·mm ⁻¹)		
	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)
TS-V	116.1	90.4	-22.1	5.4	3.6	-33.3	21.5	25.1	14.3
TS-T-A45	66.7	68.7	3.0	33.7	27.9	-17.2	2.0	2.46	23.0
TS-T-A60	36.9	41.1	11.4	16.4	13.8	-16.2	2.3	2.9	26.1
TS-T-A75	63.3	65.8	3.9	6.1	7.5	22.9	8.4	9.0	7.1

and foam core cannot be simulated effectively in finite element simulation, which leads to a slightly higher simulation value compared to the experimental value.

5 Parametric study

The experimental results could be forecasted by the FE model with enough precision. So we can use the FE model to study the effects of different parameters such

as foam density and lattice thickness. The 45° trapezoid lattice composite specimens were chosen to analyze.

5.1 Effects of foam density

Figure 17 presents the foam density influence on the 45° trapezoid lattice composite specimens and the bearing load when the face sheet and trapezoid lattice web thickness are constant. Table 8 lists the elastic ultimate bearing capacity (P_E), the elastic displacement and the

Figure 17: Displacement-load curve of specimens.

Figure 18: Displacement-load curve of specimens.

initial stiffness (K) of the 45° trapezoid lattice composite specimens with three foam densities. When the foam density was 20, 40 and $60 \text{ kg}\cdot\text{m}^{-3}$, the elastic ultimate bearing capacity were 53.2, 68.7 and 79.8 kN, respectively. The foam density increased from 20 to $40 \text{ kg}\cdot\text{m}^{-3}$ and $60 \text{ kg}\cdot\text{m}^{-3}$, the elastic ultimate bearing capacity increased by 29.1 and 50.0% respectively, and the initial stiffness increased by 21.8 and 49.0% respectively. However, the corresponding elastic displacement does not change much.

5.2 Effects of face sheet and lattice web thickness

Figure 18 presents the thickness influence of the face sheet and lattice web on the 45° trapezoid lattice composite specimens and bearing load when the foam density is constant. Table 9 lists the elastic ultimate bearing capacity (P_E), the elastic displacement and the initial stiffness (K) of the 45° trapezoid lattice composite specimens with three kinds of thickness. When thickness values are 1.2, 2.4 and 3.6 mm, the elastic ultimate bearing capacity values are 24.8, 68.7 and 101.4 kN, respectively. The

thickness increased from 1.2 to 2.4 mm and 3.6 mm, the elastic ultimate bearing capacity increased by 177.1 and 308.9% respectively, and the initial stiffness increased by 112.1 and 616.4%, respectively.

6 Finite element analysis of composite anti-collision device

The Wuhu Yangtze River Bridge is the first highway-railway cable-stayed bridge on the Yangtze River in China. The main span is 312 m, and the main span and two side spans are navigable spans. Piers No. 9–12 have the risk of ship-bridge collisions. Hence, designing anti-collision devices for piers of navigable span is vital to guarantee the safety of the bridge (Figure 19).

The floating composite anti-collision device installed on Pier No. 12 of the Wuhu Yangtze River Bridge is simulated by the finite element method. A comparative analysis about the energy dissipation effect was made between the composite anti-collision device with 45° trapezoid space lattice webs and vertical lattice webs. The structural layout of Pier No. 12 and the layout of anti-collision devices are shown in Figure 20.

Table 8: The effect of the density of foam

Specimen	Density ($\text{kg}\cdot\text{m}^{-3}$)	P_E (kN)	ΔP_1 (mm)	K ($\text{kN}\cdot\text{mm}^{-1}$)
TS-T-A45-F2-D20	20	53.2	26.28	2.02
TS-T-A45-F2-D40	40	68.7	27.9	2.46
TS-T-A45-F2-D60	60	79.8	26.5	3.01

Table 9: The effect of the thickness of the lattice

Specimen	t_s (mm)	t_w (mm)	P_E (kN)	ΔP_1 (mm)	K (kN·mm ⁻¹)
TS-T-A45-F1-D40	1.2	1.2	24.8	21.3	1.16
TS-T-A45-F2-D40	2.4	2.4	68.7	27.9	2.46
TS-T-A45-F3-D40	3.6	3.6	101.4	12.2	8.31

Figure 19: Wuhu Yangtze River Bridge. **Figure 20:** Layout of Pier No. 12 with floating composite anti-collision device: (a) head-on elevation view, (b) side elevation view, (c) planar view. (Note: Except as indicated in the figure, the remainder is calculated as cm.)

Figure 21: Numerical model of ship impact on bridge and composite anti-collision device: (a) ship – pier collision, (b) internal structure of ship bow, (c) ship–pier collision with anti-collision device, (d) the composite anti-collision device and (e) the composite anti-collision device with 45° trapezoid space lattice webs.

6.1 Numerical model

To assess the protective property of composite anti-collision device, a detailed FE model was developed using the program ANSYS/LS-DYNA. In the numerical analysis, the soil–structure interaction is considered by fixing the pile foundation. According to the calculation of the site geological conditions, the pile–soil interaction is considered in the way that the pile length was supposed to be eight times pile diameter below the mud line. An elastic material was applied to model the concrete pier, and its Young's modulus ratio and Poisson's ratio were 32.5 MPa and 0.2, respectively.

The representative ship of the Wuhu Yangtze River Bridge was a 10,000 DWT vessel. The total weight was 15,000 ton (i.e., 5,000 ton of self-weight and 10,000 ton of cargo weight). The internal structure of the ship bow is shown in Figure 21(b). The MAT_PLASTIC_KINEMATIC model [33] was applied to model the ship, and the major parameters are presented in ref. [6].

The numerical model of ship impact on the bridge is shown in Figure 21(a), and ship–pier collision with a composite anti-collision device is shown in Figure 21(c). Numerical models of the composite anti-collision device with 45° trapezoid space lattice webs and vertical lattice webs are presented in Figure 21(d) and (e), respectively. The material mode of a composite anti-collision device was referred to 4.1.2.

6.2 Simulation results

In general, the head-on collision is the most severe collision and generates maximum impact load. This article calculates the ship head-on impact of the pier with and without the composite anti-collision device under the highest water level. The initial velocity of the ship is $2.62 \text{ m}\cdot\text{s}^{-1}$.

Figure 22 shows the time history of impact force at the highest water level under three impact conditions. The

Figure 22: Load–time curve of the ship impact bridge. (Note: t represents the time duration.)

impact force of the ship without the anti-collision device is 34.21 MN. After the installation of the composite anti-collision device, the impact force is remarkably reduced. The peak impact force with a composite anti-collision device with vertical lattice webs is 9.48 MN, the peak impact force with composite anti-collision device with 45° trapezoid space lattice webs is 7.84 MN, and the peak impact force decreases by 72.3 and 77.1% respectively. The time duration is 3.67 s without anti-collision device. It is prolonged after the installation of the composite anti-collision device, and time duration is 4.19 s when composite anti-collision device with vertical lattice webs is installed, the time duration of composite anti-collision device with 45° trapezoid space lattice webs was 5.62 s, and time duration was prolonged by 14.2 and 53.1%, respectively. After adding floating composite anti-collision devices, the ship impact force is reduced significantly, the ship impact time is prolonged, and the damage to bridge piers is effectively reduced. The composite anti-collision device with 45° trapezoid space lattice webs instead of vertical latticed webs reduces the impact force of the ship by about 17.3%. The impact time was extended by about 31.1%. Therefore, the composite anti-collision device with 45° trapezoid space lattice webs has between anti-collision protection on pier.

7 Conclusion

The energy absorption performance of novel foam-filled sandwich composite structures reinforced by trapezoidal latticed webs was conducted using the experimental study and the numerical simulation analysis. The major results allow the following findings:

- (1) The experimental results indicate that the 45° trapezoidal latticed specimen has the most ideal load–displacement curve. This specimen not only avoids the problem of sudden drop in bearing capacity but also greatly improves the elastic stroke. The elastic displacement and bearing capacity after the compression stroke (P_S) of foam-filled sandwich composite structures reinforced by 45° trapezoidal latticed webs are 624.1 and 439.8%, respectively, in comparison with foam-filled sandwich composite structures reinforced by vertical lattices.
- (2) The FE model on account of experimental material properties could well forecast the crush response. The parameter analysis on account of the verified FE model demonstrated that the approach to improve the elastic ultimate bearing capacity (P_E) and the initial stiffness (K) is to widen the thickness of face sheets and lattice webs and increase the foam density.
- (3) The floating composite anti-collision device installed on pier 12 of the Wuhu Yangtze River Bridge is simulated by the finite element method. A comparative analysis about the energy dissipation effect was made between the composite anti-collision device with 45° trapezoid space lattice webs and vertical lattice webs. The results show that after changing the cross section form of anti-collision device, the peak impact force of the composite anti-collision device of 45° trapezoidal lattice webs will be reduced by 17.3%, the time duration will be prolonged by about 31.1%, and the impact protection effect of the bridge pier will be better.

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