A novel superimposed sine-wave (SSW) structure was designed and fabricated by selective laser melting (SLM) in this work. The energy absorption performance, deformation modes, and fracture mechanism of heat-treated SSW components under compression were studied. The formability was analyzed and the results showed that the SLM fabricated SSW components possessed nearly dense microstructure and smooth surface morphology. The numerical simulation model was established to show the stress distribution and deformation mechanism during compression, and the fracture morphologies of SSW components were investigated. Experimental results indicated that the SSW components exhibited a maximum crush force efficiency (CFE) of 73.06%, which was higher than most reported energy absorption structures. As the height of sinusoid 1 (H₁) increased, the energy absorption (EA) and specific energy absorption (SEA) gradually increased to 37.73 J and 8.45 J/g, respectively. Simulation results revealed that the secondary trough had a large deformation during the compression process, which greatly enhanced the load uniformity of the structure. Fracture mode of SSW components was ductile fracture due to the post heat treatment. The SSW structures had the potential to be used in aerospace, protective armor, and automotive industries.

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1. Introduction

As a typical thin-walled structure, corrugated structures have been widely used in engineering applications (e.g. aerospace, marine and automobile industries) due to their lightweight and high energy absorption efficiency [1,2]. In previous literatures, extensive studies have
been conducted to investigate the mechanical properties of single-layer and multi-layer corrugated structures using theoretical, experimental, or numerical methods. For single-layer corrugated structures, Li et al. [3] studied the deformation modes of corrugated sandwich panels through projectile impact experiments and investigated the energy absorption properties through simulation. They found that the core height of corrugated sandwich panels was the key parameter affecting the deformation mechanism. Vignjevic et al. [4] investigated the impact resistance of unidirectional corrugated panel using bird strike tests and finite element simulation method. The results showed that the impact resistance of the corrugated panel was greatly improved compared to the conventional sandwich structures. Pathirana et al. [5] indicated that the failure of corrugated panels was mainly due to structural buckling rather than material failure. Thus, they developed a semi-analytical solution to predict the influence of structural parameters on buckling, and the results revealed that the solution can accurately simulate the local buckling of the corrugated panel. Moreover, Karakoti and Kar [6] applied a novel finite element approach to uncover the deformation characteristics of the corrugated laminated composite panels. Recently, the energy absorption capability of engineering structures has become a research hotspot, and the multi-layer structures could contribute to the improvement of energy absorption [7]. Therefore, the multi-layer corrugated panels have been increasingly studied, and it has been confirmed that this type of structure has enhanced energy-absorbing ability than the single-layer corrugated panels [1,8,9]. For instance, Zhang et al. [1] developed and fabricated a series of corrugated sandwich panels with multiple layers by additive manufacturing. The failure mechanism and mechanical properties were investigated by compressive experiments and finite element simulations, which revealed that the multi-layer corrugated sandwich panel exhibited higher energy absorption capability. Hou et al. [8] investigated the multi-layer corrugated sandwich panels by experiments and numerical simulations and found that the number of layers was an important parameter for energy absorption ability and failure mechanism. In addition, Kılıçaslan et al. [9] elaborated that the buckling stress decreased and the densification strain increased with the increase of layers. However, the above studies are limited to regular corrugated panels and it is difficult to improve mechanical performance further.

The hierarchical structures mainly arise in nature and possess large length scales [10], which can enhance the physical properties of structures, such as strength, toughness, and negative Poisson’s ratio, by synthesizing the multi-scale structures. Biological materials in nature, such as bone [11], conch shells [12], bamboo [13] and tendon [14], have undergone millions of years of natural selection and have evolved structures that possess exceptional properties to provide support or protection of the bodies. The rich hierarchy of human bones [11] from the nanoscale (protein molecules) to the macroscopic physiological scale makes them tough and lightweight. Conch shells, one of the best natural body armors, have a unique three-layered hierarchical lamellar structure (outer, middle, and inner layers) and each layer consists of first, second and third-order aragonite sheets [12]. The lamellar structure of the conch shell subtly hinders the crack propagation, leading to the improvement of toughness. Bamboo is mainly composed of three hierarchical structures from macro to micro [15]. The stem of bamboo is hollow tubular and has periodic nodes (external ridge), which is the first hierarchy of macroscale. By observing the cross-sectional microstructure of bamboo, it is found that the bamboo contains longitudinal vascular bundles and parenchyma cells. Each vascular bundle is made up of two hollow vessels and phloem, which are the second and third hierarchy of microstructure, respectively [16]. The tendon is composed of closely arranged fiber bundles, which are made up of collagen molecules, and the cross-section of the tendon has up to seven levels of hierarchy, ranging from nanometers, micrometers to millimeters [14]. For the engineering application of man-made hierarchical materials, the macroscopic hierarchical frameworks date back to the Eiffel tower [10], where the large structures are made of small girders to optimize mechanical properties. Nowadays, a large number of materials are applied in hierarchical structures, such as polymer [17], metal [18] and composite [12], and hierarchical structures can be classified into lattice structures [19], thin-walled structures [20], honeycomb structures [21] and cellular structures [22]. The application of hierarchical structures greatly improves the mechanical properties of materials, for example, the discovery of metamaterials [23,24]. Thus, applying the hierarchy concept, such as multi-scale, multi-layers, and superimposition, to the design of novel corrugated panels is an effective way to develop new materials. However, no hierarchical corrugated panel has been studied so far.

In our previous studies, a bi-directionally single-sine-wave corrugated panel (DCP) was designed inspired by the mantis shrimp telson [25,26]. The deformation mode and fracture mechanism of DCP structures were studied by finite element simulations and experiments, and we found that the DCP structures possessed high specific energy absorption (SEA). However, the load uniformity of DCP structures needed to be further improved. In this paper, aiming to improve the mechanical properties of corrugated panel, we designed a novel superimposed sine-wave (SSW) structure using the hierarchy concept. The SSW structures were fabricated by selective laser melting (SLM) technology, which enables the fabrication of components with complex configurations directly from raw powder materials [27,28]. Different structural parameters of the SSW structures were considered for comparing their mechanical properties by the experiments and simulation.

2. Experiment methods and numerical models

2.1. Configuration of SSW structure

To further improve the load uniformity of bi-directionally corrugated panel (DCP) structures, a superimposed sine-wave (SSW) structure was proposed. The superimposed sine-wave was generated by superimposing the sinusoid 1 (Fig. 1a) and sinusoid 2 (Fig. 1b). The sinusoid 1 and sinusoid 2 were expressed as Eq. (1) and Eq. (2), respectively.

\[
 z_1 = \frac{H_1}{2} \sin \left( \frac{2\pi \lambda_1}{x} x - \frac{\pi}{2} \right) \tag{1}
 \]

\[
 z_2 = \frac{H_2}{2} \sin \left( \frac{2\pi \lambda_2}{x} x - \frac{\pi}{2} \right) \tag{2}
 \]

The \( H_1 \) and \( \lambda_1 \) in Eq. (1) represent height and wavelength of sinusoid 1, and the \( H_2 \) and \( \lambda_2 \) in Eq. (2) represent height and wavelength of sinusoid 2. Thus, the superimposed sine-wave (Fig. 1c) was obtained by the expression given in Eq. (3).

\[
 z = z_1 + z_2 \tag{3}
 \]

The illustrative figure of SSW was shown in Fig. 1d, and the computer-aided design (CAD) model of SSW structure (Fig. 1e) was obtained by sweeping X/Z plane superimposed sine-wave along Y-Z plane superimposed sine-wave. In addition, the length and width of SSW structure were set as 42 mm, which was three times of \( \lambda_1 \) (14 mm). As shown in Fig. 1b, the \( \lambda_2 \) was one third of \( \lambda_1 \), thus the \( \lambda_2 \) was set as 4.67 mm. In order to study the energy absorption properties of SSW structures with different structural parameters, five SSW structures were designed (Table 1). The mass of the SSW structure determines the material distribution, which in turn affects its energy absorption performance. Therefore, different thickness (T) were designed to maintain the same mass of these five SSW structures.
A CAD model of SSW structure (e) was obtained by sweeping X-Z plane superimposing sine-wave along Y-Z plane superimposing sine-wave. The superimposed sine-wave on the X-Z plane, which was generated by superimposing the sinusoid 1 (a) and sinusoid 2 (b). The illustration of SSW, and the computer-aided design (CAD) model of SSW structure (e) was obtained by sweeping X-Z plane superimposing sine-wave along Y-Z plane superimposing sine-wave.

Table 1

| No. | \( \lambda_1 \) (mm) | \( \lambda_2 \) (mm) | \( H_1 \) (mm) | \( H_2 \) (mm) | \( T \) (mm) | \( H \) (mm) |
|-----|---------------------|---------------------|----------------|----------------|------------|------------|
| SSW-1 | 14                | 4.67                | 2/3            | 10/3           | 0.40       | 8.40       |
| SSW-2 | 14                | 4.67                | 8/3            | 4/3            | 0.47       | 8.47       |
| SSW-3 | 14                | 4.67                | 2              | 2              | 0.56       | 8.56       |
| SSW-4 | 14                | 4.67                | 8/3            | 4/3            | 0.66       | 8.66       |
| SSW-5 | 14                | 4.67                | 10/3           | 2/3            | 0.73       | 8.73       |

The spherical AlSi10Mg powder was used as the raw materials in this work, and the mean particle size of AlSi10Mg powder was 30 \( \mu \)m (Fig. 2a). The reason for choosing AlSi10Mg is that it has the characteristics of low density and good mechanical properties, and it is widely used in aerospace and automobile fields [29,30]. The SLM process was performed by the SLM system developed by Nanjing University of Aeronautics and Astronautics. The SLM system was equipped with a YLR-500 ytterbium fiber laser (IPG Laser GmbH, Burbach, Germany), a chamber with argon gas, a powder spreading device, and a process control computer. SLM parameters have great influence on formability of samples [31,32], and were set as follows based on our previous work [33]: scanning speed 2200 mm/s, laser power 400 W, hatch spacing 50 \( \mu \)m, and layer thickness 30 \( \mu \)m. The long-exposure images of laser beam interacting with AlSi10Mg powder are shown in Fig. 2b. The block support was used for the SSW structures in SLM processing to improve the formability of overhanging parts. An “island” laser scanning strategy with an island size of 5 \( \times \) 5 \( \mu \)m\(^2\) and scan direction rotation of 37° between neighboring two layers was applied for SLM, as shown in Fig. 2c. The as-fabricated SSW components with different structural parameters (Table 1) are shown in Fig. 2d. In according with the ASTM F3301-18a standard, the as-fabricated SSW components were heat treated for stress relief at 285 °C temperature for 120 min, and cooled in the furnace to ambient temperature. For microstructure observation, the specimens were polished and etched by Keller reagent (HF 2 mL, HCl 3 mL, HNO\(_3\) 5 mL, and distilled water 190 mL). The optical microscopy (OM, Olympus Corporation, Japan) was obtained to apply low-magnification microstructures and characterize the densification behavior. The surface morphology was observed by scanning electron microscope (SEM, FEI-Quanta 200, USA). The compressive tests were performed using CMT5205 testing machine (MTS Industrial System, China) at room temperature, and the crosshead velocity was fixed at 0.2 mm/min. Three samples for each SSW structure were prepared for the compression experiment to reduce experimental error. A video camera (SONY, Japan) was used to capture and record the deformation of specimens during all compressive tests. After the compressive tests, the fracture morphologies were studied by SEM.

2.2. Experiment methods

In order to further understand the deformation mechanism and stress distribution of SSW structures under compression, the numerical simulations were conducted. The ANSYS LS-DYNA was used as simulation software and the elastic linear strain-hardening material of SSW structure in this model was set as AlSi10Mg. The mechanical properties of AlSi10Mg were presented in Table 2 [25]. As shown in Fig. 3, the finite element model contained a top plate for displacement, a bottom plate for fixing and the SSW structure was sandwiched in the middle of two plates. The top and bottom plates were set as rigid bodies and the mesh type of SSW structure model was set as tetrahedron with the size of 0.3 \( \times \) 0.3 mm\(^2\). The displacement was applied to deform the model and the value was set as the thickness of SSW structure.

2.3. Numerical simulation

To evaluate the mechanical performance of SSW components, several indicators were employed in this study as follows [34]:

Energy absorption (\( EA \)): the area enclosed by the force-displacement curve to a given displacement and the coordinate axis:

\[
EA(d) = \int_0^d F(x)dx
\]

where \( F(x) \) is the compressive force, and \( d \) is the compressive displacement. The displacement was set to be densification displacement in this study.
Specific energy absorption (SEA): defined as the energy absorbed per unit mass. For energy absorption structures with the same mass, the larger the SEA value is, the more energy is absorbed.

\[
SEA(d) = \frac{EA(d)}{m}
\]  

where \(EA(d)\) is the absorbed energy by the compression process defined in Eq. (4) and \(m\) is the structure mass.

Crush force efficiency (CFE): For energy absorption structures, a higher value of CFE is desired.

\[
CFE = \frac{MCF}{PCF} \times 100\%
\]  

where \(PCF\) denotes the peak crushing force and \(MCF\) denotes the mean crushing force. The \(MCF\) is expressed as follows:

\[
MCF = \frac{EA(d)}{d}
\]  

where \(EA(d)\) is the absorbed energy by the compression process defined in Eq. (4) and \(d\) is the given displacement.

Densification displacement (\(d_0\)): the compressive displacement where the structure reaches densification. The energy absorption structure cannot dissipate the energy after densification and loses its energy absorption capacity. Therefore, \(d_0\) is the endpoint of displacement for calculating energy absorption.

Table 2

| Properties       | Young's modulus E/ GPa | Yield stress \(\sigma_y\)/MPa | Ultimate stress \(\sigma_u\)/MPa | Poisson's ratio \(\nu\) |
|------------------|------------------------|-------------------------------|-------------------------------|-----------------------|
| Value            | 68.9                   | 260                           | 411                           | 0.33                  |

Fig. 2. Selective laser melting process of SSW components. (a) Morphology of AlSi10Mg powder. (b) Long-exposure images of laser-powder interaction. (c) Schematic of island scanning strategy applied for SLM. (d) As-fabricated SSW components with different structural parameters (Table 1) and corresponding models.
3. Results and discussions

3.1. SLM formability analysis

The SLM fabricated SSW components and the SEM images of edge morphology are shown in Fig. 4. The SEM images show the edge morphology of one wavelength of sinusoid 1 (three wavelengths of sinusoid 2). It can be found that the thickness of SSW components gradually increased from SSW-1 to SSW-5, which accorded with the thickness variation of designed CAD models (the red lines in Fig. 4). In addition, a small amount of un-melted powder adhered to the surface of the components, especially on the down-facing surface. The reason can be concluded that the SSW structures are overhanging structures in the SLM process. The underside of the overhanging structure lacks solid support, and the bottom powder is not completely melted during the laser process, thus the un-melted powder bond to the underside of the overhanging structure. Fig. 5a and b show the OM images of the cross-section of as-fabricated and heat-treated SSW-3 component along the building direction. As can be seen from Fig. 5a, the track-track overlapping traces were clear, which were molten pool boundaries formed during SLM process. After heat treatment, the track-track overlapping traces disappeared (Fig. 5b), suggesting that the heat treatment could homogenize as-fabricated AlSi10Mg microstructure and improve mechanical properties. The SEM image of the surface morphology of an SLM fabricated SSW-3 component was exhibited in Fig. 5c. From the OM and SEM images, it can be concluded that the SSW components with nearly dense microstructure and smooth surface morphology were fabricated.

3.2. Mechanical properties

The energy absorption performance of SLM fabricated SSW components was studied by compression tests. Fig. 6a shows the force-displacement curves of five SSW components, and the snapshots obtained during the compressive test of SSW-3 are shown in Fig. 6b-e. In Fig. 6a, the toe region in the initial portion of each force-displacement curve represented the deformation before full contact between the indenter tip and the SSW component. The toe region also included the failure of the residual block support (structural support to mitigate the failure of overhanging solid) built in the SLM process. It can be found that the curve of SSW-1 kept increasing until densification, while the SSW-2, SSW-3, SSW-4, and SSW-5 curves can be divided into four stages, namely elastic deformation (region 1), force drop (region 2), plateau (region 3), and densification (region 4). For SSW-2, the slope of the elastic loading segment (region 1) was between 0.3 and 1.4 mm displacement and the elastic region was followed by force drop region (region 2), which ranged from 1.4 mm to 1.9 mm displacement and was caused by the fracture of structure. The plateau region ranged from 1.9 mm to 2.48 mm displacement. The force-displacement curve of SSW-3 was similar to that of SSW-2, with an elastic loading segment of 0.2–1.4 mm displacement and a plateau region of 2.5–4.4 mm displacement. The arrows in the Fig. 6a were correlated with the images of Fig. 6b-e, which represented the elastic deformation (region 1), force drop (region 2), plateau (region 3), and densification (region 4), respectively. For force-displacement curves of SSW-4, the elastic deformation region ranged from 0.4–1.7 mm displacement and the plateau
region ranged from 3.8–5.8 mm displacement. For force-displacement curves of SSW-5, the elastic deformation region ranged from 0.2–1.9 mm displacement and the plateau region ranged from 4.3–6.9 mm displacement. To compare the mechanical properties of SSW structures, various mechanical indicators ($d_0$, PCF, and MCF) were listed in Table 3. For SSW-1, SSW-2, SSW-3, SSW-4, and SSW-5, densification displacement ($d_0$) increased as the increase of height of sinusoid 1, revealing higher energy absorption capability. The MCF increased from 0.46 kN (SSW-1) to 5.46 kN (SSW-5). The PCF exhibited a similar trend to $d_0$, which can be attributed to the increase of thickness of SSW structures. As shown in Table 1, the thickness ($T$) of SSW structures gradually increased from 0.40 mm to 0.73 mm, which improved the toughness of the structures and made it not easy to be damaged.

Fig. 7a shows the energy absorption ($EA$) and specific energy absorption (SEA) of five SSW structures. The densification stage (region 4) of the compressive force-displacement curves represents that the SSW structures have been destroyed, which is a process of material compaction and has no energy absorption capacity. Therefore, only the stages before the displacement of $d_0$ were considered in the calculation of $EA$ and SEA. As shown in Fig. 7a, the energy absorption ($EA$) of five SSW structures increases from 0.06 J to 37.73 J and the specific energy absorption (SEA) increases from 0.01 J/g to 8.45 J/g. $EA$ and SEA are proportional to the height of sinusoid 1 ($H_1$) and inversely proportional to the height of sinusoid 2 ($H_2$), which indicates that sinusoid 1 plays a major role in energy absorption. Fig. 7b shows the crush force efficiency (CFE) of these five SSW structures. It can be seen from Fig. 7b that the CFE increases until reaching its peak value (73.06%) at SSW-3, then the CFE decreases. It can be concluded that the SSW-3 has the greatest load uniformity (highest CFE). The reason can be attributed to the fact that the compressive curve of the SSW-3 structure has the longest plateau region of all the compressive curves of the five SSW structures.

Fig. 8 shows the crush force efficiency comparison among the SSW structures investigated in this work and energy absorption structures in other literature. The CFE range includes both results of compression experiments and simulations. For energy absorption structures, higher CFE value represents higher load uniformity, and the data in Fig. 8 indicate that the load uniformity of SSW structures is competitive with other energy absorption structures.

### Table 3

Compression characteristics of SSW components.

| Indicators | SSW-1 | SSW-2 | SSW-3 | SSW-4 | SSW-5 |
|------------|-------|-------|-------|-------|-------|
| $d_0$ / mm | 0.13  | 2.48  | 4.42  | 5.83  | 6.91  |
| PCF / kN   | 1.11  | 2.73  | 3.88  | 6.08  | 9.51  |
| MCF / kN   | 0.46  | 1.95  | 2.83  | 3.78  | 5.46  |

Fig. 6. Compressive properties of SSW components fabricated by SLM. (a) The Force-Displacement compressive curves of SSW-1, SSW-2, SSW-3, SSW-4, and SSW-5. (b-e) The snapshots of four typical stages of SSW-3 marked in (a).
3.3. Stress distribution and deformation mechanism

Fig. 9a-e show the stress distribution results of SSW-1, SSW-2, SSW-3, SSW-4, and SSW-5, respectively, and the insets in Fig. 9a-e show the stress at the secondary trough (red circle position). Fig. 9f is the stress value of secondary trough showed in Fig. 9a-e. From SSW-1 to SSW-5, the stress value of the secondary trough gradually decreased (from 608 MPa of SSW-1 to 103.8 MPa of SSW-5), leading to more uniform distribution of compressive stress across the panel as can be seen from the contour colors (Fig. 9a-e). In order to obtain a complete stress distribution contours, the fracture boundary conditions of the material were not applied into the simulation, so the stress shown in the Fig. 9 would be higher than the ultimate stress of the AlSi10Mg material. The uniform distribution of stress contributed to the absorption of energy, thus, the $EA$ and $SEA$ increased from SSW-1 to SSW-5. The crush force efficiency ($CFE$) of the SSW structure closely related to the stress distribution. When the structure was compressed, the stress concentration occurred at the secondary trough of the SSW structures, which represented the transmission of force was hindered. Therefore, the secondary trough obstructed the transmission of force and dissipated...
most of the force, which improved the load uniformity. The secondary trough of SSW-3 had the largest portion of large stress area, which hindered the force diffusion and dissipated most of the force and thus had the highest CFE value.

To understand how the SSW structures substantially improved mechanical performance, the simulation results of the deformation stages (stage I-IV) of SSW-1, SSW-3, and SSW-5 are exhibited in Fig. 10. Points A are the secondary trough and Points B are the crest. As shown in Fig. 10a, the deformation process of SSW-1 shows typical global buckling collapse mode. From the stage I to stage IV, the compressive stress was first concentrated at points B, which made the crest flattened. As the compressive displacement increased, the wall buckled and tilted toward the middle, which caused low load uniformity. In contrast, the SSW-3 showed a fully folded deformation mode (Fig. 10b). The walls adjacent to Points B did not buckle from stage I to stage IV, and the angle between the walls at the Points A gradually decreased from 81° to 62°, which indicated that the secondary trough produced a large deformation during the compression process and further led to the localization of plastic deformation. According to the deformation stages of SSW-5 (Fig. 10c), the secondary trough did not bring significant changes to the deformation behavior of the structure. Previous studies [2,25] on the deformation of corrugated panel have confirmed that the fully folded deformation mode is beneficial to the energy absorption and crush force efficiency of the structures. Thus, the CFE of SSW-3 is higher than that of SSW-1 and SSW-5. The secondary trough of SSW structures ensured that the CFE of the SSW structures in this work increased by...
6.5% compared to the bi-directionally corrugated panel in previous literature, which was 55.8%–68.6% (Fig. 8). The typical fracture morphologies of SSW structures with different structural parameters are shown in Fig. 11 to further elaborate the fracture mechanism. Fig. 11a–e show the SEM fracture morphologies of SSW1–5, respectively, and Fig. 11f shows the high magnification SEM image of the area marked in Fig. 11c. As can be seen from the SEM images, the fracture morphology was mainly composed of dimples and some opened-up pores (Fig. 11f), indicating that the fracture mode of SSW components was ductile fracture. The reason for this fracture morphology may be that the crack first initiates from the pores and then gradually propagated outward, forming ductile fracture [47].

4. Conclusion

In this paper, novel superimposed sine-wave (SSW) structures were fabricated by selective laser melting (SLM) process and the post heat treatment was performed. The forming quality of SSW components was analyzed and the compression experiments were conducted to reveal the mechanical properties. Stress distribution of SSW structures during compression was simulated using the finite element method and the deformation mechanism was analyzed. Finally, to further understand the fracture mechanism of SSW components, the fracture morphologies were elaborated. The main conclusions are listed as follows:
1. As the height of sinusoid 1 ($H_1$) and thickness ($T$) increased, the energy absorption (EA) and specific energy absorption (SEA) gradually increased to 37.73 J and 8.45 J/g, respectively. The reason was that the decreased stress of secondary trough led to the compressive stress being more evenly distributed across the panel and further contributed to better energy absorption ability.

2. The crush force efficiency (CFE) of SSW-3 reached peak value of 73.06% and a method to improve the CFE was proposed, that was to design self-similar secondary structures on the energy design. The stress concentration areas, which appeared on the secondary trough of SSW structures, obstructed the transmission of compressive force and were positive to improve the CFE of SSW structures.

3. The compression fracture mode of SSW structures was all ductile fracture due to the heat treatment.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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