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# Experimental Study of Buckling of Reinforced Conical Composite Shell Under Hydrostatic Loading

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**K E Y W O R D S**

Composite conical shells;
Buckling;
Strength-to-weight ratio;
Statistical optimization;
RSM.

**A B S T R A C T**

Cone shells due to their special aerodynamic shape are the main component for air-space transport and submarine structures. The application of composite materials in these structures leads to achieving lower strength-to-weight ratios. Due to the type of application, most of these structures are under external pressure. The purpose of this paper is to achieve an empirical relationship between buckling pressures and the impact of various factors on the strain. The four factors that are going to be evaluated in this article are cone size, number of layers, number of layers of longitudinal reinforcement (Stringer), and number of circular reinforcement (Ring). To achieve this goal truncated composite cone samples, longitudinal and circular reinforcements are made of woven glass fiber with epoxy resin. The experiments are based on the RSM method in optimization. The results of this paper showed that the longitudinal reinforcements are not effective on buckling pressure.

## 1. Introduction

Many researchers for many years focused on the buckling of cylindrical and conical shells and determining the critical buckling load of structures, and determining their critical load has been the base of most of the research. This phenomenon threatens very thin structures that are under force or compressive stresses. Structures such as columns, plates, and shells are common structures in many diverse applications in different industries.

Buckling of shells is mainly discussed in the fields of mechanical engineering, marine science and marine structures, civil engineering, chemical engineering, and aerospace engineering. It can be used for example in the design of steel columns, tanks under variable suction, longitudinal pipes in boilers for the passage of hot gases, submarine hulls and research submarines, some of the structural components of ships, spacecraft design, components of nuclear reactors, supersonic aircraft and automotive industries.

Needs in the aerospace industry led to expansion in the use of composite materials. Lightweight, high strength, and high rigidity are favorite characteristics of designers. Nowadays composites have widespread and advanced users in our products.

While the properties of composites are better than other materials available to designers, Specific problems and challenges in understanding the structural behavior such as construction, failure, and damage during maintenance are associated with them. Over the past decade, composite materials are widely used in engineering applications from aircraft bodies to tennis rackets. Due to the high Strength-to-weight ratio and flexibility, composite materials have many fans.

Also among the rotating shells, cone shells have a special place. These structures are very suitable due to their aerodynamic shape and are used mostly in the nose and for connecting two cylindrical shells. These structures due to their shape have numerous applications in the aerospace and marine industries. Minimum weight is an important factor in the aerospace

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industry. Due to this, strengthening the structures and reducing overall weight will be very important.

Many types of research have been done on the issue of buckling conical shells. Seide [1,2] studied the buckling of conical shells under axial loading. Singer [3] investigated the buckling of conical shells against external axial symmetry pressure. Buckling of reinforced conical shells subjected to hydrostatic pressure has been studied by Singer.

Singer [3] studied the orthotropic buckling of conical shells. Weigarten and Seide [4] studied the stability of conical shells subjected to axial compressive load and external pressure. Those authors considered the stability of conical shells subjected to internal pressure and axial force.

In an article, Ross [6,5] investigated experimentally and numerically reinforced isotropic conical shells (metal). He reinforced three steel shells with ring reinforcements and compared them with numerical results.

In an article, Sofiyev [7] investigated the orthotropic single-layer cone buckling with variable thickness. In his paper, the buckling of conical shells of variable thickness for truncated orthotropic composite cones subjected to external uniform pressure, which varies with time, has been studied.

In other articles, Sofiyev [8,11,12] the vibration and stability behavior of freely supported FGM conical shells. Also, he studied the vibration and stability of non-homogeneous orthotropic conical shells [9], Buckling and vibration of shear deformable functionally graded orthotropic cylindrical shells [10], and the free vibration of sandwich truncated conical shells [14].

Ning Zhang and his colleagues studied Stability, Buckling, and Free Vibration Analysis [13] and Mohamad S. Qatu and his colleagues investigated recent research advances in the dynamic analysis of composite shells [15].

In this paper the effects of the four factors: cone size, number of layers, the number of longitudinal reinforcement (Stringer), and the number of circular reinforcement (Ring) on the truncated cone-shaped composite subjected to external loading have been studied and in terms of buckling pressure and weight has been optimized.

## 2. Construction of Composite Samples

There are several methods for manufacturing composite parts. Each of these methods has advantages and disadvantages. Various techniques such as hand lay, filament winding, vacuum, pressure, resin injection, etc. have been developed for this purpose. For example, the filament winding method can be counted as one of the most industrialized production methods for making composite parts.

In this method, it is possible to achieve high precision. Among the problems of this method is its relatively high cost. Some Methods such as vacuum, pressure, and resin injection have the advantage of achieving a high percentage of fiber volume but in these methods, producing many parts is not possible. The hand lay-up method has unique features including a relatively low cost, the possibility of manufacturing a large part, a large number of copies, low geometric precision, low-strength components, and the low volumetric percentage of fibers.

Due to the above description, it is essential to choose a good method for the construction of the cone. To do this, the manually layering technique was chosen as a conventional manufacturing method. In this method, we need a model for shaping samples. The model used was made of wood. Wooden models that were used in this study are shown in Fig. 1.

As shown in Fig. 1, to enhance the finished surface of the models, the putty has been applied to the wood. In Table 1 nominal geometric dimensions of the sample have been shown. The dimensions, which represent the geometric parameters of a cone, are expressed in Fig. 2. Thus, vertex angle of the cones, (γ) was considered 30°.

**Fig. 1.** wooden models used for making samples

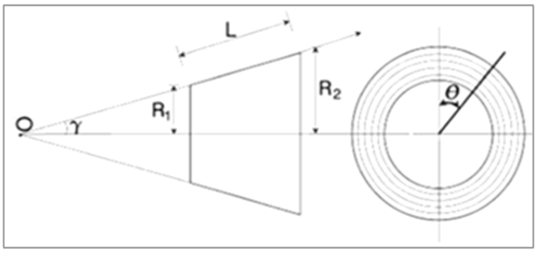


**Fig. 2.** Geometric parameters of a cone

**Table 1.** Nominal dimensions of the specimens

| Cone size | Small Radius R1(m) | Big Radius R2(m) | lateral height L(m) | L/R1 |
|---|---|---|---|---|
| Small | 0.055 | 0.11 | 0.11 | 2 |
| Medium | 0.055 | 0.137 | 0.17 | 3 |
| Big | 0.055 | 0.165 | 0.22 | 4 |

Reinforcing fibers in this paper are textured woven fabrics of glass fibers with plate patterns. The density of the fibers is 225 grams per square meter. EEW-185 epoxy resin was used which was manufactured by Huntsman Germany. The resin is cooked with a hardener with the brand name Jfamyn. For the production of composite resin and the hardener were mixed with a ratio of 1 to 10. Given the time it takes to bake at the ambient temperature (20 degrees Celsius), the cooking time was about 4-5 hours.

Thus, whit smearing the above mixture to these clothes and applying different numbers of layers of glass fabrics on the model, the different thicknesses can be achieved. In this work, the specimens were formed with two, three, and four layers. Fig.3 shows the cut cloths and shows the final pieces made.

**Fig. 3.** above: cut cloths, down: composite samples

### 2.1. Mechanical Properties of Composite Material

Composite materials due to their anisotropic nature have different mechanical properties in different directions. Because of the type of cloth used, they will have the same properties in two perpendicular directions (in textiles directions). Table 2 shows the mechanical properties obtained from tensile tests on one of the main directions of the composite.

**Table 2.** Mechanical properties of composites and resins

| Material type | Modulus of elasticity (GPa) | Yield stress (MPa) | Density (kg/m3) |
|---|---|---|---|
| composite | 15 | 229 | 2010 |
| cooked Resin (Pure) | 4 | 130 | 1200 |

### 2.2. The Actual Dimensions of the Specimens Built

The important issue in experimental tests is the lack of full geometric compliance with the nominal size of the sample made. In these cases, there will always be some distortion and imperfect with the exact amounts. In this study, thickness variation and deviations from circularity have been studied. Due to the methods used, the imperfect nature of the sample is random. Thus, standard deviation from the mean value is used. The general definition of standard deviation is shown in Eq. (1).

$$\zeta = \frac{\sqrt{(\bar{x} - x_i)^2}}{n} \tag{1}$$

In the above equation is the mean value of the variables, is the value of each variable, and n is the total number of variables. In the above equation, one can choose the variables either the structural thickness in different places or different diameters of structures in different directions where the thickness of the fibers is divided by the layer thickness. The total thickness of fibers is 0.1 mm. To facilitate the identification of specimens a simple coding scheme is used: The character to the left refers to the size and the Character to the right refers to the number of layers used in the fabrication of the samples. For example, S4 is a small specimen with four layers.

## 3. Structural Reinforcements (Ring & Stringer)

In the construction of Structural reinforcements, the same material of the truncated cone is used and for their shape, a rectangular cross-section is used. The thickness was chosen so that the number of layers of the reinforcements was two times the number of layers of the cone. Their width was 0.05 of an edge length for each reinforcement. It would be better if the reinforcements were integrated into the whole structure but due to limitations in production, it was not possible. The connection between the Structural reinforcement and the main structure was made using epoxy adhesive under a local loading and the temperature was 50 degrees Celsius.

## 4. Design of Experiments

Four key parameters were varied in each cone. Two parameters were concerning the main structure including the number of layers and the size of the cone. Two other parameters were concerning the reinforcements including the number of circular and longitudinal reinforcements. The levels for each variable are shown in table 3.

**Table 3.** Factors and their levels (uncoded)

| | size | Number of layers | Longitudinal reinforcements (Stringer) | Circular reinforcements (Ring) |
|---|---|---|---|---|
| The notation in Eq. | a | b | c | d |
| Low | Small (-1) | 2 | 0 (-1) | 0 |
| Average | Medium (0) | 3 | 4 (0) | 1 |
| high | Large (1) | 4 | 6 (1) | 2 |

To optimize the design of experiments a CCD design is used which is one of the standard forms of the RSM method according to those three levels for each parameter is considered. Using software for the design of experiments (Minitab) and by applying this method, the number of experiments was 31.

## 5. Experiments

For testing the specimens, a Fixtures was made in the laboratory of Metal forming in the Faculty of Mechanical Engineering in Khaje Nasir e Toosi University which is shown in Fig. 4. The Fluid used for loading was air and a compressor supplied the loading pressure. To lower the rate of decline in the loading and make static conditions, two inlet valves were used at the same time. Parts were installed inside the fixture by silicone adhesive and for the smaller diameter of the cones; a rigid polyethylene cap was used so that the parts were completely sealed. Then the pressure slowly increased. The average pressure increase was one Bar/Min.

Data were taken with a pressure gauge. The precision of pressure gauges was about 20 bar. There were three ways to recognize the Buckling moment: 1- the sound of the specimen 2- an instantaneous reduction in pressure and 3- the observation. Then the pressure in that first mode of buckling was occurred, was recorded.

**Fig.4.** Sample testing device

## 6. Results

In Table 4 the experimental design used in this study and the values obtained from the experiments are shown. Using ANOVA, the data were analyzed. The relative influence of each parameter on the buckling pressure was determined.

The results of the analysis of variance show that the longitudinal reinforcement factor was insignificant. This means that the longitudinal reinforcement, regardless of shape, size, and the number of layers does not affect the strength of the overall structure against external hydrostatic pressure. This type of reinforcement may be effective at thrust loads on structures.

Figures 5 to 8 show the effect of the other 3 parameters on Pressure. Adequacy of the model is shown in Fig. 5.

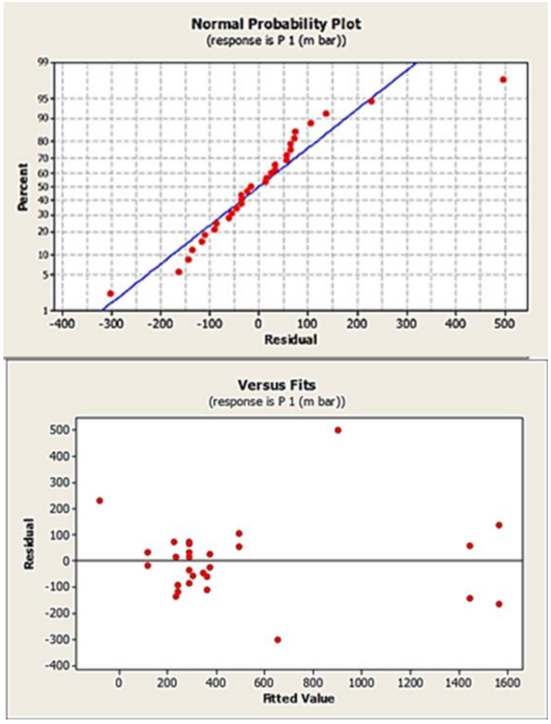


**Fig. 5.** residual Scatter plot buckling pressure analysis

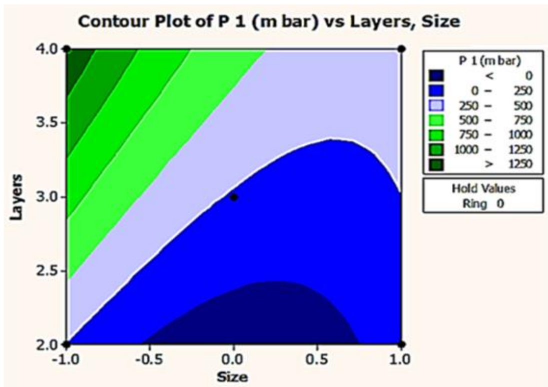


**Fig.6.** Diagram of buckling pressure for factors size and number of layers, the ring factor is zero

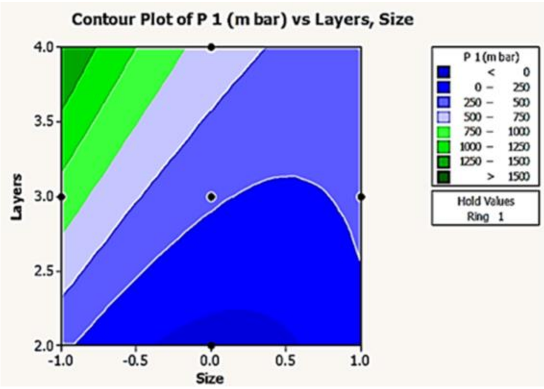


**Fig. 7.** Diagram of buckling pressure for factors size and number of layers, the ring factor is one

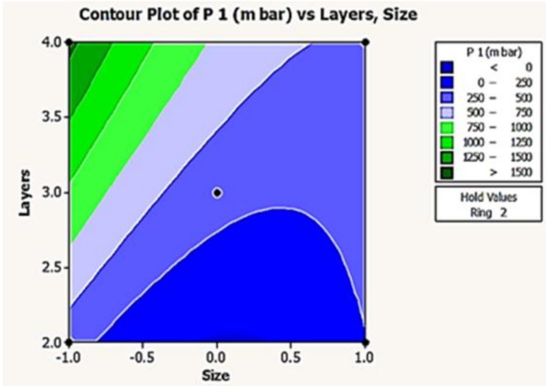


**Fig. 8.** Diagram of buckling pressure for factors size and number of layers, the ring factor is two

**Table 4.** The design of experiments and the result

| StdOrder | RunOrder | Size | Layers | Stringer | Ring | Resin (gr) | Buckling pressure (Mbar) |
|---|---|---|---|---|---|---|---|
| 3 | 10 | -1 | 4 | -1 | 0 | 120 | 1300 |
| 16 | 11 | 1 | 4 | 1 | 2 | 600 | 600 |
| 1 | 12 | -1 | 2 | -1 | 0 | 60 | 125 |
| 31 | 13 | 0 | 3 | 0 | 1 | 258 | 350 |
| 11 | 14 | -1 | 4 | -1 | 2 | 120 | 1400 |
| 20 | 15 | 0 | 4 | 0 | 1 | 344 | 350 |
| 2 | 16 | 1 | 2 | -1 | 0 | 300 | 150 |
| 17 | 17 | -1 | 3 | 0 | 1 | 90 | 1400 |
| 28 | 18 | 0 | 3 | 0 | 1 | 258 | 250 |
| 7 | 19 | -1 | 4 | 1 | 0 | 120 | 1500 |
| 18 | 20 | 1 | 3 | 0 | 1 | 450 | 250 |
| 29 | 21 | 0 | 3 | 0 | 1 | 258 | 300 |
| 30 | 22 | 0 | 3 | 0 | 1 | 258 | 250 |
| 10 | 23 | 1 | 2 | -1 | 2 | 300 | 250 |
| 23 | 24 | 0 | 3 | 0 | 0 | 258 | 300 |
| 5 | 25 | -1 | 2 | 1 | 0 | 60 | 150 |
| 24 | 26 | 0 | 3 | 0 | 2 | 258 | 300 |
| 15 | 27 | -1 | 4 | 1 | 2 | 120 | 1500 |
| 12 | 28 | 1 | 4 | -1 | 2 | 600 | 550 |
| 14 | 29 | 1 | 2 | 1 | 2 | 300 | 100 |
| 26 | 30 | 0 | 3 | 0 | 1 | 258 | 200 |
| 9 | 31 | -1 | 2 | -1 | 2 | 60 | 250 |

According to ANOVA, the following regression equation for the resistance of reinforced composite cones against hydrostatic pressure was achieved. This equation is valid for the buckling pressure:

$$P = -868.632 + 409.201(a) + 365.278(b)$$
$$+59.77(d) + 317.244(a)^2 - 235.937(a) \times (b)$$

One of the goals of this study was to optimize the strength-to-weight ratio of structures. During manufacturing before and after strengthening, the weights of all specimens were measured. The difference in weight was included as a factor in the DOE. Increasing the amount of longitudinal and circular reinforcement has a direct relation to the weight of the structure.

The regression equation for the weight is shown below:

$$\begin{aligned} Weight &= 82.5684 + 10.4097(a) \\ &- 55.3291(b) - 6.07639(c) \\ &+ 15.6111(d) + 10.2863(b)^2 \\ &+ 11.1875(a) \times (c) + 8.81250(a) \times (d) \\ &+ 7.06250(b) \times (c) \end{aligned}$$

In Figures 9 to 11, the changes in weight based on the 4 factors: size, number of layers, the number of longitudinal reinforcements, and the number of circular reinforcements are shown. Graphs, respectively, show the changes in weight for the minimum, average, and maximum of other factors. The adequacy of the model for the weight is shown in Fig. 9.

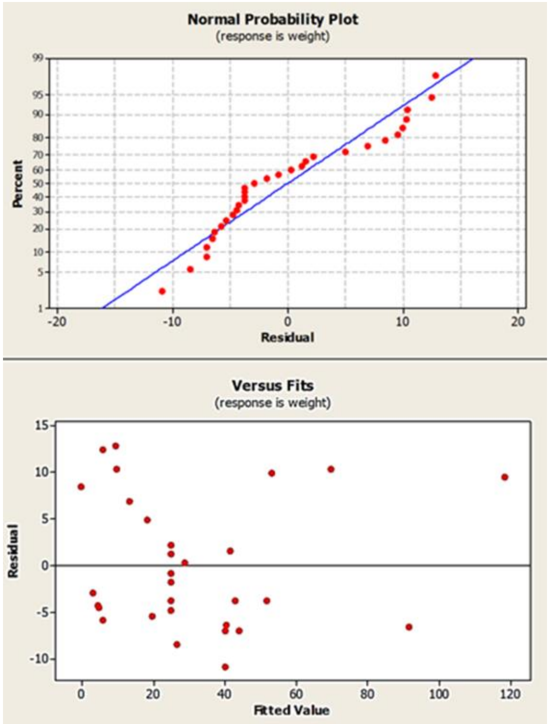


**Fig. 9.** residual Scatter plot for weight analysis

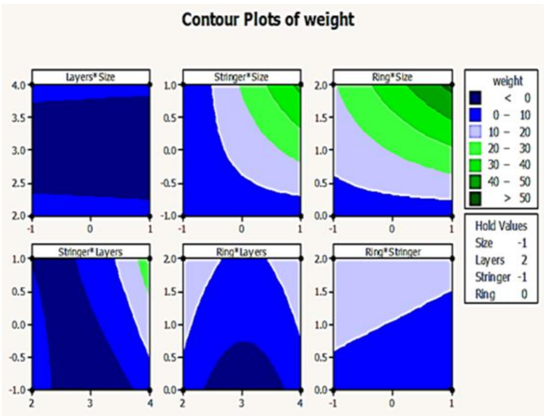


**Fig. 10.** weight plots for the minimum value of other factors

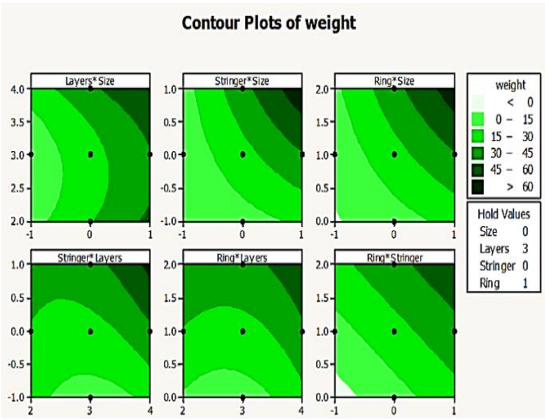


**Fig. 11.** weight plots for the mean value of other factors

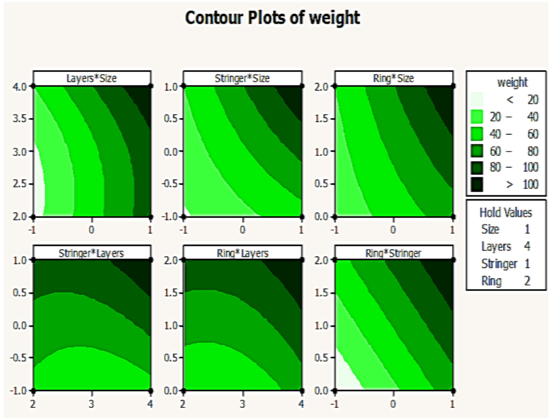


**Fig. 12.** weight plots for the maximum value of other factors

As expected, with increasing all the facts, the weight increases but weight gain is not good for aerospace uses. An increase or decrease in the weight of each piece must be compared according to the pressure it can bear. Therefore, one should optimize the buckling pressure and the weight simultaneously. Therefore, an optimization for the buckling pressure and the weight was done and the optimum for them was found.

### *6.1. Optimization Analysis of Buckling Pressure and Weight*

According to the analysis done, the best optimum for all four factors is shown in Table 5.

It is noteworthy that the desirability factor is 0.956463, which is very good. The optimization chart is shown in Fig. 13.

It shows that to achieve maximum static pressure resistance and low weight factors should be at high levels. With the 3.18 g increase in weight, the buckling pressure of 1563.72 mbar can be reached.

**Table 5.** The amount of factors for optimum buckling pressure and weight

| Factor | Optimized amount |
|---|---|
| Size | S |
| Layer | 4 |
| Stringer | 0 |
| Ring | 2 |

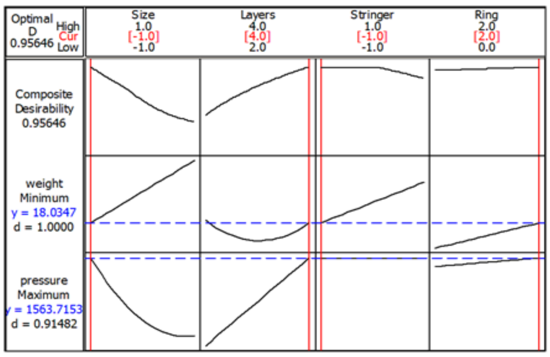


**Fig. 13.** Optimization graph for buckling pressure (P) and weight

## 7. Conclusion

The results of the analysis of variance showed that the longitudinal reinforcement factor was ineffective. This means that the longitudinal reinforcement, regardless of shape, size, and the number of layers in the structure, does not affect the strength of the structure against external hydrostatic pressure this type of reinforcement may be effective against thrust loads on structures.

From the results of the analysis of variance, a regression equation for buckling to pressure was achieved. This equation is very close to the results of the experiments. According to this equation, the effect of each factor on the buckling pressure was determined. The impact of these factors is such that, in general, with an increasing number of layers ($\frac{R_1}{t}$), decreasing the size ($\frac{L}{R_1}$), and increasing the number of circular reinforcements; buckling pressure goes up. It was considered that the longitudinal reinforcement does not affect the number and location of buckling modes.

## Conflicts of Interest

There was no conflict of interest between the authors.

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