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STRUCTURAL BEHAVIOR OF UMBILICALS – PART II: MODEL-EXPERIMENTAL COMPARISONS

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ABSTRACT

A set of tests was performed in a non-armored Steel Tube Umbilical (STU), including pure pressure loading, constant and variable tension loads and combinations of constant and cyclic bending moment and tension. Tests were made for pressurized and non pressurized conditions. Strains were measured with strain gages attached to the external surface of selected tubes. Instrumentation was performed in four windows that were opened on the umbilical outer sheath to provide access to the tubes. Besides the strains, tension, internal pressure and imposed angle were measured. Comparisons with results obtained using the model presented in Part I, [1], are presented for different load conditions.

INTRODUCTION

This paper is companion to another one, Part I, [1], presented at the same Conference, addressing aspects of a fully research and development program undertaken in the structural behavior of umbilicals. The present paper is focused on model-experiment comparisons.

Nowadays the offshore industry usually relies on numerical tools in order to perform design tasks. In the particular case of umbilicals, from cross-section definition to fatigue evaluation, several design software are used.

One of the tasks involved during the umbilical design process is to assess strains and stresses states in its elements due to an external set of loads. As shown in Part I, [1], this type of calculation is complex and there is not a complete accepted numerical code in the market.

For this reason, umbilical manufacturers develop their own tool based on mathematical models. This tool, however, needs to be validated against experimental results in order to provide confidence and/or feedback information to the mathematical model (such as hypotheses validation) and/or to verify the ranges of applicability of the model.

This is exactly the path covered by Part I, [1], and the present paper. Part I took care of the mathematical model description, summarizing reference [2]. The present paper presents the experimental arrangement, results and also comparisons to the mathematical model, and is based on reference [3].

UMBILICAL DESCRIPTION

The umbilical sample used in the test is a non armoured steel tube umbilical. It is composed by:

- one central steel tube of internal diameter 38.1mm and wall thickness 3.0mm with a polyethylene coating of thickness 1.0mm;
- three steel tubes of internal diameter 25.4mm and wall thickness 2.0mm;
- nine steel tubes of internal diameter 12.7mm and wall thickness 2.6mm;
- low-density polyethylene fillers to provide suitable arrangement of the steel tubes and avoid direct contact between them;
- high-density polyethylene outer sheath;
  All steel tubes are made of super duplex steel (SAF 2507).

The umbilical cross-section is shown in Figure 1.

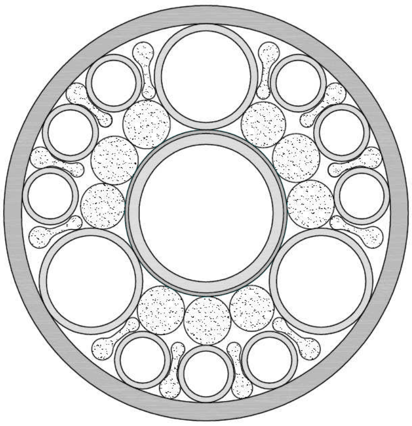

Figure 1 – Umbilical cross-section: one 38.1mm internal diameter / 3.0mm wall thickness steel tube at the center; three 25.4mm internal diameter / 2.0mm wall thickness and nine 12.7mm internal diameter / 2.6mm wall thickness steel above. Copyright by Prysmian Cables & Systems.

As per the classification given in Part I, [1], this umbilical has a central tube and a heterogeneous layer type "B" above.

EXPERIMENTAL ARRANGEMENT

Test Bench Description

The test bench can accommodate a total 4249mm sample, including end-fittings (armour pots). In this case, as one can see in Figure 2, the armour pots length is 502mm; the total free umbilical length is 3245mm.

One of the bench end-plates is fixed and the other one is connected to hydraulic actuators that impose tension and bending angles at the end, see Figure 4.

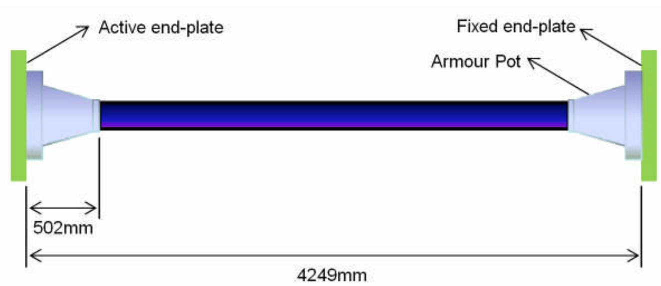

Figure 2 – Test bench and umbilical sample length.

Test bench is capable of imposing tension, angular rotation and pressure in the steel tubes. Test load ranges are shown in Table 1.

Table 1 – Test load ranges

Load	Tension (kN)	Pressure (psi)	End Angle (deg)	Curvature * (1/m)
Minimum	10.0	0	-1.5	0
Maximum	90.0	3000	+1.5	0.023

*Due to end rotation.

A partial view of the test bench showing one of the sample umbilical ends with the armour pot may be seen in Figure 3.

Figure 3 – Partial view of the test bench showing the umbilical sample and one of the armour pots connected to the fixed end-plate.

Another partial view, see Figure 4, shows the hydraulic actuators that impose tension and angles at the end-plate and leads to curvatures in the umbilical sample.

Figure 4 – Partial view of the test bench showing the hydraulic actuators at the active end-plate.

It is important to state that the fixed end-plate allows for umbilical rotations and only reacts at tension loads.

Umbilical Instrumentation

In order to measure the strains in the steel tubes due to the loads applied by the test bench, several strain gauges were attached at certain points along the umbilical length. In these points, windows were opened on the external sheath to allow access to the tubes. The locations of the windows are presented in Figure 5.

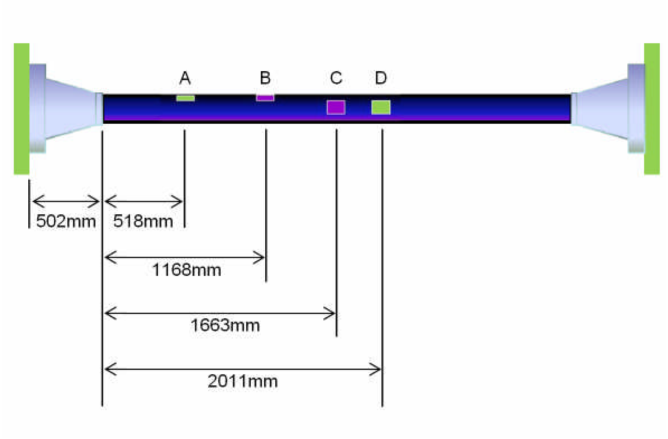

Figure 5 – Instrumentation windows locations.

Each window was opened in a spot were access to a 25.4mm internal diameter tube would be achieved. In addition to that, surrounding 12.7mm internal diameter tubes were instrumented as well. The instrumented tubes for each window are presented in Figure 7.

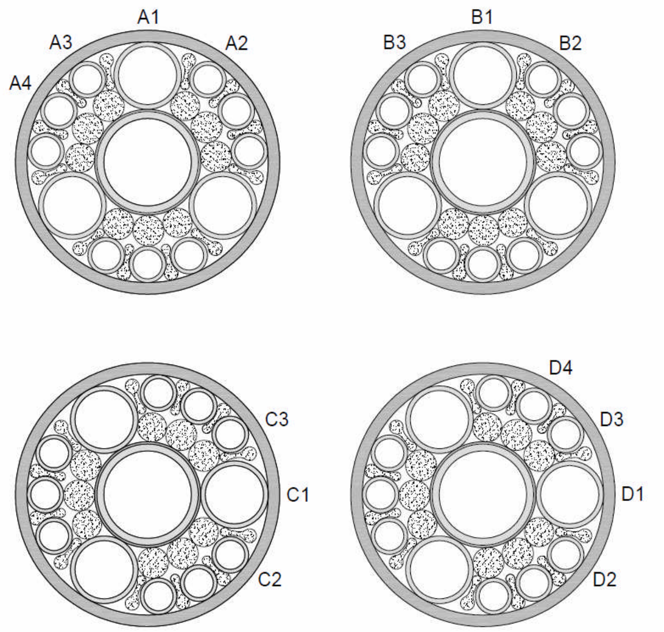

Figure 6 – Instrumented tubes in each window.

Figure 7 shows a detail of one of the instrumented windows. Notice the strain gauges attached to one 25.4mm internal diameter tube and to two 12.7mm internal diameter tubes.

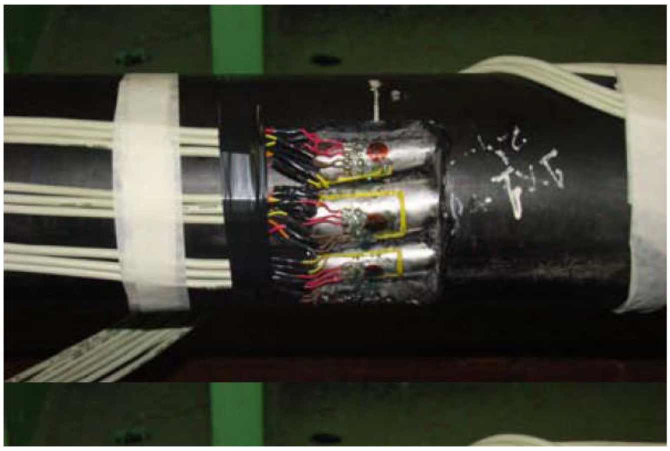

Figure 7 – Instrumentation window detail. Three tubes instrumented with strain gauges: upper and lower are 12.7mm internal diameter tubes; central is a 25.4mm internal diameter tube.

Since the test bench imposes curvature by means of an end rotation, it was found necessary to measure the curvature of the umbilical. For this purpose, a set of LVDTs were attached to several locations along the umbilical. Those sensors, which location are depicted in Figure 8, allow the deflection of each point to be measured. A curve fit with a third order polynomial is performed, since analytical solutions to beam deflection result in a polynomial of this order. An example is depicted in Figure 9. With the fitted curve, the curvature can be determined.

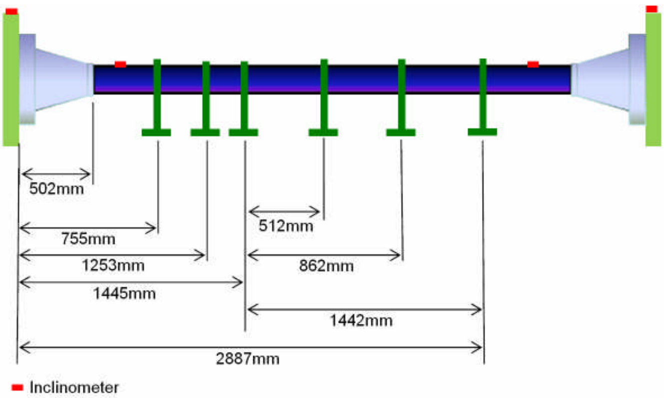

Figure 8 – LVDT locations.

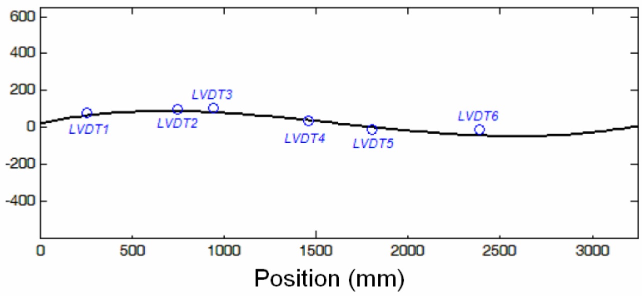

Figure 9 – Example of curve fit with LVDT measures.

EXPERIMENTAL RESULTS AND COMPARISON TO MATHEMATICAL MODEL

This section presents results from the experiment, as well as a comparison with the mathematical model presented in Part I, [1], for the same loads.

The stresses presented here were calculated from measurements of tubes A1 and A2 (see Figure 6). Those tubes were selected because they belong to window A, which presents larger curvature due to their position, furthest from the bending central line (see Figure 3, where the window presented there is window A), for which larger bending stresses are expected.

The presented data refer to axial stress, since this is the main component on the external surface of the tube. A representative subset of the complete test matrix was selected to illustrate the results encountered in the comparisons. These can be found in Table 2 and Table 3.

Table 2 – Summary test results and comparison with mathematical model [1] for the 25.4mm internal diameter tube, axial stress

Loads			Axial Stress 25.4mm ID Tube (MPa)		
Tension (kN)	Pres. (MPa)	Curv. (1/m)	Test	Model	Diff. (%)
28.51	20.71	0.0001	49.18	57.60	14.6%
29.39	19.39	0.0148	99.38	104.0	4.4%
40.01	0.00	0.0141	56.14	57.80	2.9%
60.44	0.00	0.0076	47.55	51.70	8.0%
60.35	0.00	0.0140	70.28	68.60	-2.4%
60.57	0.00	0.0214	101.50	98.20	-3.4%
59.86	20.78	0.0004	60.66	74.80	18.9%
60.44	19.83	0.0080	91.16	95.90	4.9%
60.47	19.46	0.0149	110.08	113.10	2.7%
60.67	19.81	0.0225	145.09	137.00	-5.9%
91.41	0.00	0.0141	80.52	84.90	5.2%
91.22	20.85	0.0006	72.13	92.10	21.7%
91.55	19.52	0.0151	120.77	129.90	7.0%

Table 3 – Summary test results and comparison with mathematical model [1] for the 12.7mm internal diameter tube, axial stress

Loads			Axial Stress 12.7mm ID Tube (MPa)		
Tension (kN)	Pres. (MPa)	Curv. (1/m)	Test	Model	Diff. (%)
28.51	20.71	0.0001	31.98	29.20	-9.5%
29.39	19.39	0.0148	61.88	60.40	-2.4%
40.01	0.00	0.0141	36.32	41.20	11.8%
60.44	0.00	0.0076	40.86	40.60	-0.6%
60.35	0.00	0.0140	48.84	50.80	3.9%
60.57	0.00	0.0214	67.10	62.6	-7.2%
59.86	20.78	0.0004	45.19	44.50	-1.5%
60.44	19.83	0.0080	64.38	58.80	-9.5%
60.47	19.46	0.0149	74.52	67.90	-9.8%
60.67	19.81	0.0225	85.48	83.80	-2.0%
91.41	0.00	0.0141	60.59	65.50	7.5%
91.22	20.85	0.0006	58.39	59.80	2.4%
91.55	19.52	0.0151	87.17	82.80	-5.3%

It can be seen from the results on the tables that for both tubes, the 25.4mm and 12.7mm internal diameter ones, the results agree fairly well, being the differences smaller than 10% in most cases. In the few cases where the differences are larger than 10%, the mathematical model presented larger stress values than measured, which is considered acceptable, since it is on the safe side.

Based on the results of the experiment, a series of graphs were plotted, comparing experimental and numeric results in different cases. In Figure 10 and Figure 11 the stresses are plotted against the curvature for pressurized and non pressurized tubes, showing good correlation in both cases.

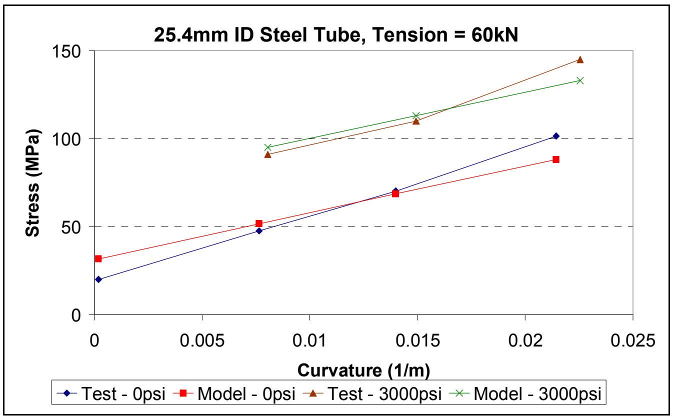

Figure 10 – Stresses on the 25.4mm internal diameter tube for varying curvature at tension 60kN.

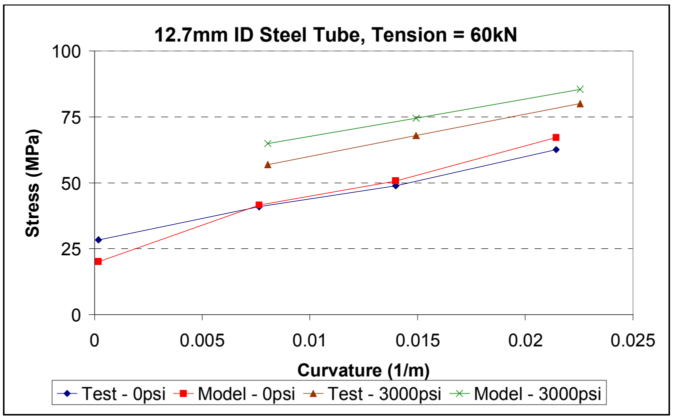

Figure 11 – Stresses on the 12.7mm internal diameter tube for varying curvature at tension 60kN.

The graph in Figure 12 shows that the mathematical model is conservative for the calculation of stresses due to tension on the 25.4mm internal diameter tube for the pressurized and not bent condition. In Figure 13, results are shown for the 12.7mm internal diameter tube. In this case, the mathematical model may be said slightly conservative for low values of tension.

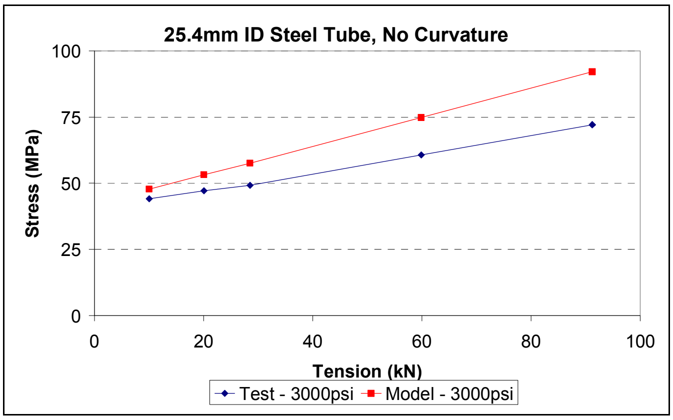

Figure 12 – Stresses on the 25.4mm internal diameter tube for varying tension at zero curvature.

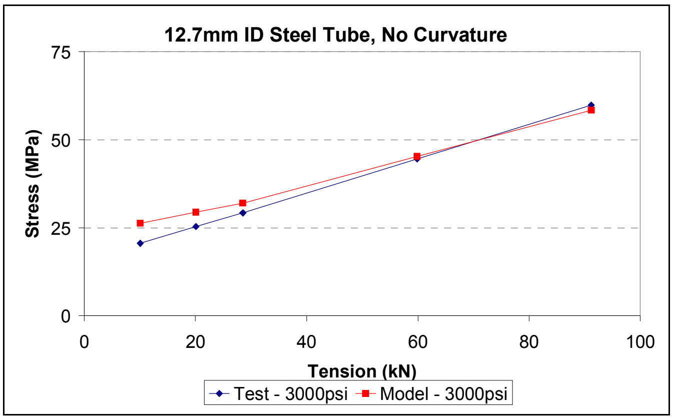

Figure 13 – Stresses on the 12.7mm internal diameter tube for varying tension at zero curvature.

The previous graphs are re-plotted in Figure 14 and Figure 15, now for the non pressurized condition, with the umbilical bent to a 0.015/m curvature.

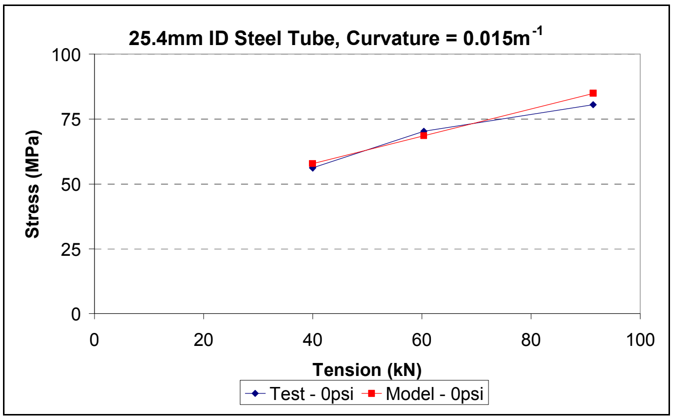

Figure 14 – Stresses on the 25.4mm internal diameter tube for varying tension at zero pressure.

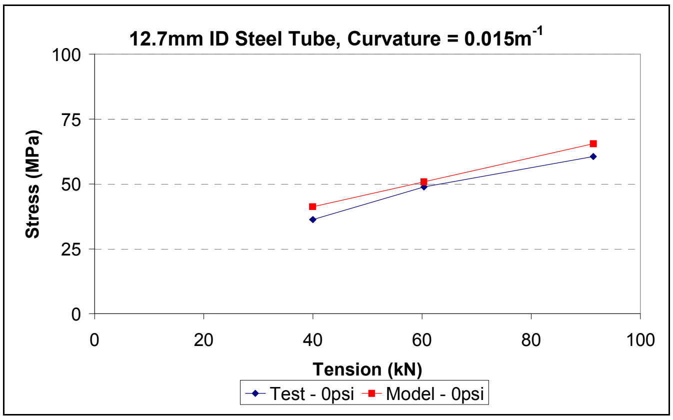

Figure 15 – Stresses on the 12.7mm internal diameter tube for varying tension at zero pressure.

Finally, Figure 16 and Figure 17 depict results varying the internal pressure of the tubes, for different tension and curvature conditions.

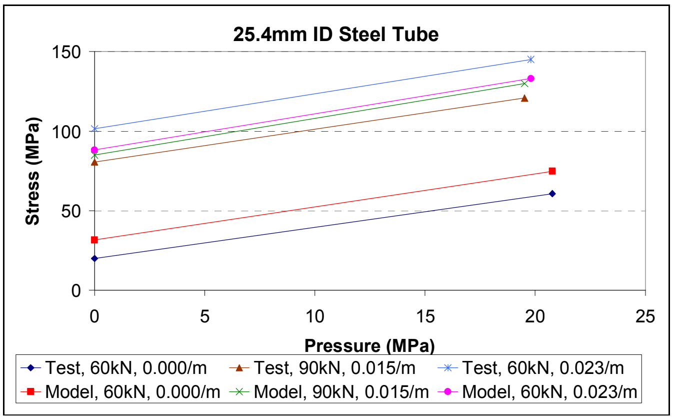

Figure 16 – Stresses on the 25.4mm internal diameter tube plotted against internal pressure.

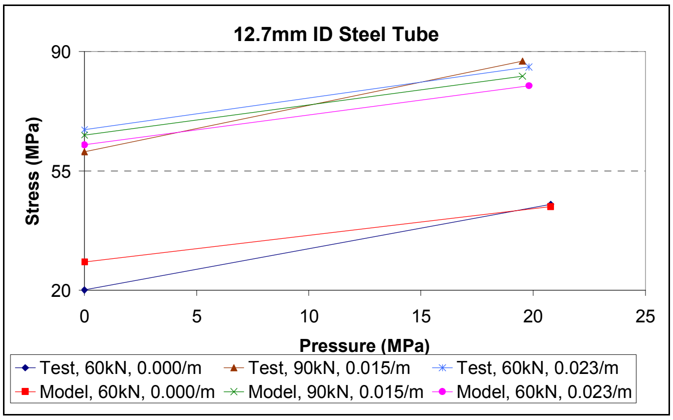

Figure 17 – Stresses on the 12.7mm internal diameter tube plotted against internal pressure.

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

The comparison of experimental data to model results indicates that the model can capture both qualitative and quantitative response aspects within the tested range.

Differences between experimental data and model results are within an acceptable level considering, from one side, all the uncertainties and deviations that are intrinsic to any experiment and, from the other side, all hypotheses and simplifications included in the mathematical model.

Some limitations related to the experiment are the relatively short umbilical sample, which may cause end-effects not taken into account in the mathematical model, and also the range of applied external loads.

In terms of tension, the umbilical weight in water, flooded, is 132.5N/m and thus the maximum 90kN from the experiment corresponds to the weight of 680m of umbilical in water. If dynamics and catenary (or lazy-wave) shape are included, this value may be low.

In terms of curvature, the maximum $0.023m^{-1}$ represents a bending radius of 43m, a typical value for fatigue load cases, but still far from the most extreme conditions.

As for internal pressure, umbilicals may be designed for a working pressure of 5000psi to 10000psi.

Nevertheless, despite these limitations which should be worked out in a later stage, the results are encouraging.

ACKNOWLEDGMENTS

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