# EXPERIMENTAL AND NUMERICAL STUDIES OF LARGE-SCALED FILAMENT WOUND T700/X4201 COMPOSITE RISERS UNDER BENDING

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## Abstract

Risers are a key component of ocean exploitation currently dominated by designs utilizing steel. Risers are used in a number of different applications and are used as a transport to and from the ocean floor. Globally there is a gradual increase in the benefits of deepwater exploration, going further and further from the shore, which will continue due to the wealth of minerals and hydrocarbons on or under the seabed. Previous studies have shown that the use of standard metallic risers at greater depths isn't feasible due to the weight of these materials. Fiber-reinforced polymer composite materials are one potential candidate to replace steel due to their high strength to weight and durability but little is known about their behavior in these conditions over the long operating life, 20 years or more, expected from risers. Bending is one of the most critical modes that risers typically experience during their operation under the effects of sea current and wave impacts. Since composite materials are susceptible to transverse loadings due to their relatively low transverse-to-axial stiffness ratio, it is essential to understand and analyze the deformation mechanisms of composite risers undergoing bending induced by transverse loads. Herein, we investigate the response of a two-meter filament wound Toray T700/Epotech X4201 composite risers by bending tests and model their damage mechanisms through a progressive failure framework based on stiffness reduction method. Experimental and numerical analyses of filament wound pipes with different composite laminates such as the $[90]_{56}$, $[45/-45]_{28}$ layup are presented. Nonlinear responses of the T700/X4201 composite pipes are observed which may be dominated by shear failure and delamination between the plies. To account for such nonlinearities and to correctly capture the damage mechanisms, effective damage models for fiber and matrix tension and compression failure modes are proposed for the composite risers. Validated numerical models with test results can thus be combined with a computational homogenization scheme for subsequent global-local analyses of risers.

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## 1. Introduction

Carbon-fiber reinforced polymeric (CFRP) composite materials emerges as a potential offshore riser material over 20 years ago [1], inspired by its superior strength and lightweight. Composite risers are increasingly exploited in deepwater applications with intentions to offer higher oil and gas production at greater water depth over conventional steel risers. Composite risers may exhibit multiple failure mechanisms due to the composite anisotropy and the complexity of load conditions under deepwater. Accurate prediction of composite riser responses therefore becomes challenging. Current offshore industry guidelines such as DNV suggest a safety factor of 15 to 50 [2] to be employed in the design and analysis of production composite risers. A good understanding on the composite riser behavior becomes essential to help reduce the safety factors for risers. Various experimental programs have commenced over the past decades to examine the composite riser applicability in deepwater. Some of the works include Salama et al. [3, 4], Sparks and Odru [5], Gibson [6], Ramirez and Engelhardt [7], Rodriguez and Ochoa [8]. Most of the studies analyzed the buckling responses and possible delamination-type failures of composite pipes under bending [9-15] since composite risers are mainly subject to transverse loads induced by the sea current, wave and hydrodynamic pressures during their operation. Recent efforts are also made on linking the global and local analyses of risers [16-20]. Despite significant experimental and numerical efforts examining the mechanical performance of composite risers in the past years, full-diameter studies of composite risers are still insufficient and thus requiring more contribution to the field. A comprehensive review on design, experimental programs and mechanics of composite risers has been recently provided by Pham et al. [21].

In this work, we investigate the bending performance of filament wound T700/X4201 composite risers through multi-level experimental procedure and a progressive failure modeling method. Two-meter T700/X4201composite pipes manufactured by filament winding technique are tested under bending and their coupon materials are also extracted to measure the filament wound composite properties. The mechanical properties of the T700/X4201 material in principal material directions are measured, serving as initial inputs for the simulation models. Progressive failure analyses of the T700/X4201 filament wound materials and corresponding pipes are then performed and the predicted failure patterns are verified again experimental data. Starting with simple composite layups, the intended work aims to derive a validated simulation tool which can be used to effectively estimate the behavior of composite risers under deepwater conditions and potentially extended to failure prediction of composite risers with complicated layups under static and variable amplitude fatigue loadings.

## 2. Experiment

### 2.1. Description of full-diameter CFRP riser tests and coupon tests

Carbon Fiber Reinforced Polymer (CFRP) pipes of 2000mm in length and 220mm internal diameter and a total wall thickness of 11.2mm were tested under bending. The continuous filament winding process was employed to fabricate the pipes using carbon fiber roving and anhydride epoxy resin with the carbon weight fraction of 75.7%. Two different laminate designs with stacking sequences of $[45/-45]_{28}$ and $[90]_{56}$ were used with the winding angle representing the angle between the fiber direction of each ply and the longitudinal axis of the pipe and the subscripts representing the total number of plies. Fig. 1 shows the riser pipes with two different layups. Table 1 presents the dimensions and the material specification of the filament wound T700/X4201 pipes as provided by the manufacturer.

To evaluate the mechanical properties of T700/Epoxy X4201 filament wound pipes, small scale CFRP coupons were also fabricated from the pipes and tested following ASTM standards. The coupons were cut in the longitudinal direction of the pipe with similar layups and have the dimensions of 250mm x 30mm x 1.2mm as shown in Fig.2.

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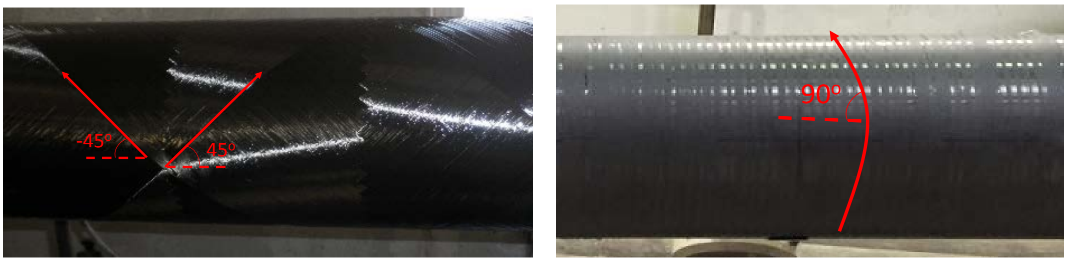

(a) $[45/-45]_{28}$ pipe (b) $[90]_{56}$ pipe

**Figure 1.** Riser pipe with differernt layups

**Table 1**. Material specifications of Toray T700 and Epotech X4201

| | |
|---|---|
| Toray T700 | Tensile strengthen:4,900MPa<br>Tensile modulus:230GPa<br>Density:1.8g/cm3 |
| Epoxy X4201 | Glass transition temperature:148.7℃<br>Tensile strength：59.7MPa<br>Tensile modulus:2.712GPa<br>Density:1.13g/cm3 |
| Layup A | $[45/-45]_{28}$ |
| Layup B | $[90]_{56}$ |
| Oven curing | 90℃/2h+130℃/2h+150℃/5h |
| Weight fractions | Epoxy:24.3%; Carbon fiber:75.7% |
| Pipe dimension | Interal diameter:220mm; Thickness:11.2mm |

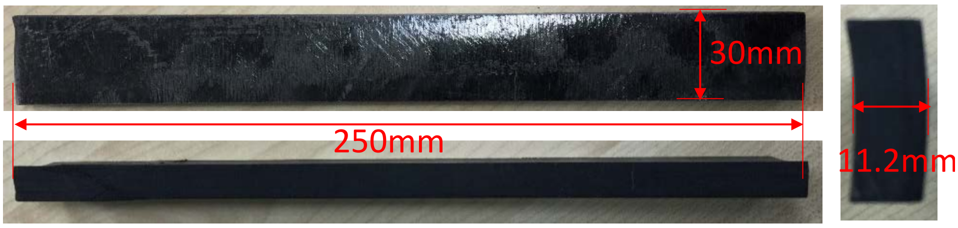

**Figure 2.** Dimension of coupon specimen

## 2.2. Bending behavior of CFRP risers

The $[45/-45]_{28}$ and $[90]_{56}$ filament wound pipes were tested under 4-point bending with a total span of 1800 mm and a shear span region of 600 mm. During the test, the load is measured by a load cell mounted on the actuator. Linear variable differential transducers (LVDTs) are fastened to the selected positions in order to monitor the displacement at different locations along the pipe. Strain gauges are attached on the pipe surface to measure the strain reading (Fig. 3).

Table 2 shows the test results of the bending tests. The maximum load for the $[45/-45]_{28}$ pipe is 126.1kN and that for the $[90]_{56}$ pipe is 41.2kN. Fiber orientation imposes a strong influence on the ultimate strength of CFRP pipes under bending. The ultimate bending resistance of the $[45/-45]_{28}$ pipe is over 3 times that of the $[90]_{56}$ pipe. Fig. 4(a) shows the load-displacement curves of the two pipes. The load-displacement curve of the $[45/-45]_{28}$ pipe exhibits a linear response followed by a nonlinear unloading behaviour. The pipe shows a residual strength up to 80MPa after failure. Figure 4(b) plots the load-midspan displacement curves of the $[90]_{56}$ pipe. Overall, the load-midpan displacement

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curves manifest a brittle behavior and the load carrying capacity depletes rapidly beyond the ultimate value, accompanied by a popping sound in the test.

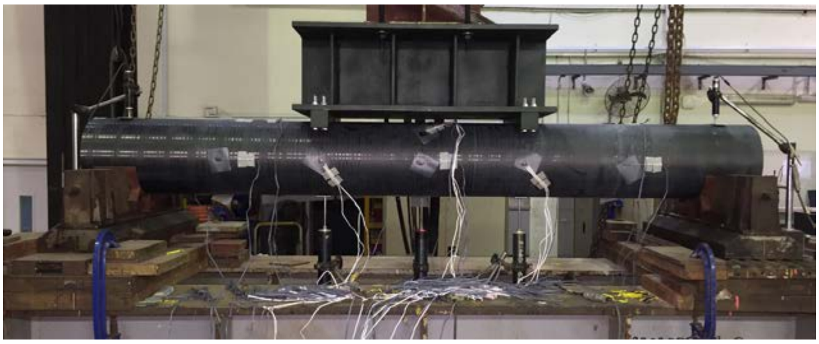
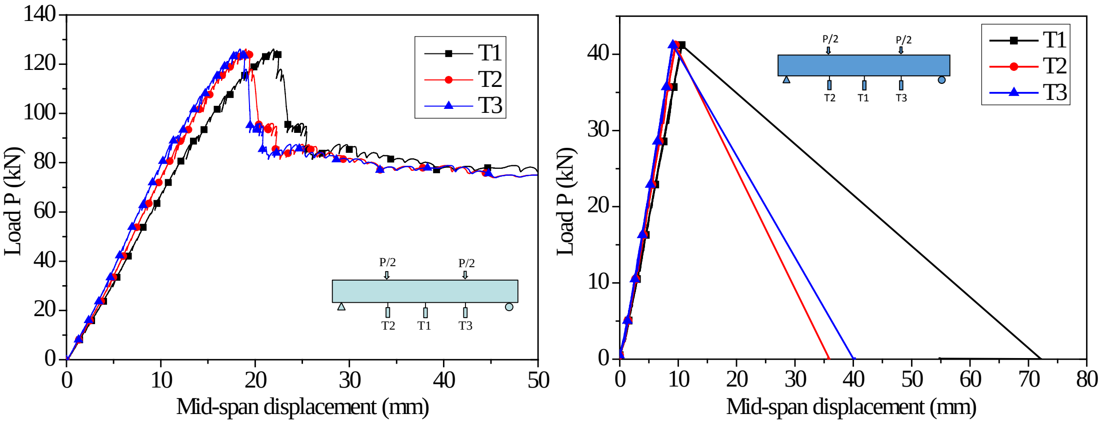


**Figure 3.** Test setup and instrumentations of riser pipe under 4-point bending test

**Table 2**. Test results of the CFRP pipes under 4-point bending.

| Layup | Dimension (mm) | Ultimate load (kN) | Failure mode |
|---|---|---|---|
| Layup: $[45/-45]_{28}$ | CHS208.8×11.2×2000 | 126.1 | local indentation<br>+global bending |
| Layup: $[90]_{56}$ | CHS208.8×11.2×2000 | 41.2 | fracture failure |



(a) $[45/-45]_{28}$ layup (b) $[90]_{56}$ layup

**Figure 4.** Load-midspan displacement of riser pipes under bending tests

## 2.3. Stress-strain responses and failure modes of CFRP coupons in tension

Three CFRP coupon specimens for each layup were extracted from each tested riser pipe. The detailed dimensions and test results are shown in Table 3 and Table 4. The monotonic tensile tests were conducted using a 1,000 kN MTS testing machine equipped with hydraulic grips for all specimens in accordance with ASTM D3039 [22]. Coupons are instrumented with a 50 mm extensometer and strain gauges to measure displacement and strains, as shown in Fig. 5. The machine load, extensometer and strain gauge data were collected continuously during the test using a data acquisition system.

The failure of $[45/-45]_{28}$ specimens is observed with delamination at the eary stage, followed by fiber failure in 45 and -45 degree, as shown in Figure 5. Figure 6 demonstrates the tensile stress-strain responses of the $[45/-45]_{28}$ coupons. The measured tensile strength of the $[45/-45]_{28}$ coupons is 146.7MPa. The stress-strain curves reveals three consecutive stages, including the linear, nonlinear and the hardening stage. In contrast, the failure behavior of the $[90]_{56}$ specimens is brittle with a lower tensile strength, and failure is mainly observed in the transverse direction (Fig. 5). Fig. 6 plots the stress-strain curves of the $[90]_{56}$ coupons showing a sharp drop in the curves. The max tensile strength obtained for the $[90]_{56}$ coupons is 16.5MPa.

**Table 3**. Test results of $[45/-45]_{28}$ CFRP coupons

| Item | Specimen type | Thickness t (mm) | Width b (mm) | Length L (mm) | Ultimate load (kN) | Ultimate stress (MPa) |
|---|---|---|---|---|---|---|
| T45-1 | Layup $[45/-45]_{28}$ | 11.3 | 31.5 | 250.2 | 50.2 | 141.2 |
| T45-2 | | 11.2 | 31 | 250 | 49.1 | 140.9 |
| T45-3 | | 11.2 | 30.2 | 250.1 | 53.5 | 158.1 |
| Average | | | | | 50.9 | 146.7 |

**Table 4**. Test results of $[90]_{56}$ CFRP coupons

| Item | Specimen type | Thickness t (mm) | Width b (mm) | Length L (mm) | Ultimate load (kN) | Ultimate stress (MPa) |
|---|---|---|---|---|---|---|
| T90-1 | Layup $[90]_{56}$ | 11.5 | 31 | 251.4 | 6.2 | 17.4 |
| T90-2 | | 11.5 | 30.9 | 251.1 | 5.2 | 14.6 |
| T90-3 | | 11.5 | 28.5 | 250.5 | 5.7 | 17.5 |
| Average | | | | | 5.7 | 16.5 |

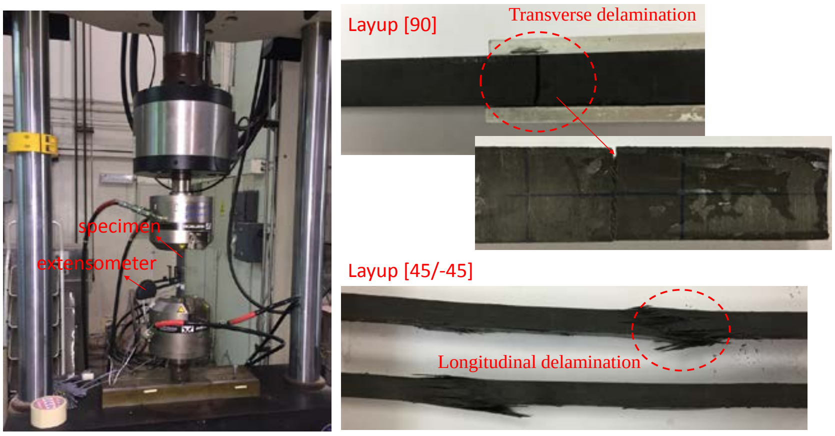


**Figure 5.** Test setup and faillure modes for CFRP coupon tensile test

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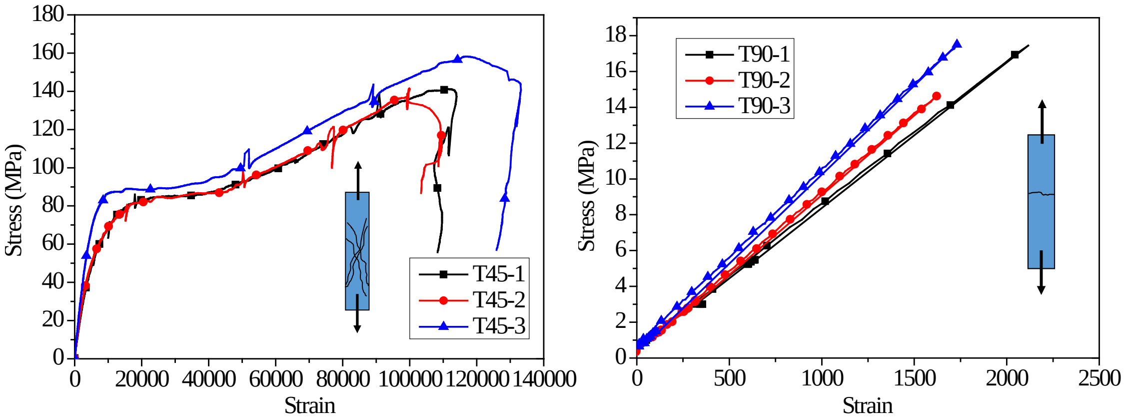


**Figure 6.** Stress-strain curves of CFRP coupon with $[45/\text{-}45]_{28}$ and $[90]_{56}$ layups

## 3. Finite Element Model

The FE models of the coupon and the pipe are shown in Fig. 7. The material property degradation method [23, 24] is used and implemented in user material subroutine (UMAT) to capture the damage and failure mechanisms of the filament wound coupons and pipes that are observed in the experiment. Hashin failure criteria are employed to predict the damage initiation of the matrix and the fiber as followings:

Tensile fiber failure:
$$\frac{\sigma_{11}}{X_t} = 1, \quad \sigma_{11} > 0 \tag{1}$$

Compressive fiber failure:
$$\frac{\sigma_{11}}{X_c} = -1, \quad \sigma_{11} < 0 \tag{2}$$

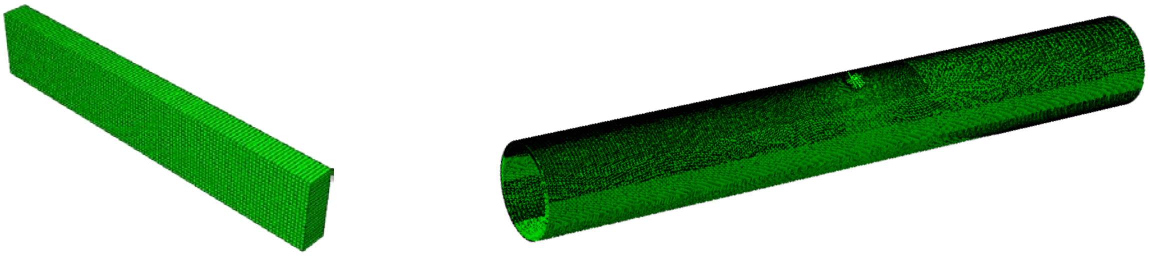
Tensile matrix (transverse direction) failure:
$$\left(\frac{\sigma_{22}}{Y_t}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 = 1, \quad \sigma_{22} > 0 \tag{3}$$

Compressive matrix failure:
$$\left[\left(\frac{Y_c}{2S_{23}}\right)^2 - 1\right]\frac{\sigma_{22}}{Y_c} + \left(\frac{\sigma_{22}}{2S_{23}}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 = 1, \quad \sigma_{22} < 0 \tag{4}$$

After damage initiation, damage progression in the matrix and fiber is modeled based on the smeared crack models to describe the linear softening rule of the corresponding stiffness. The elastic moduli of composite materials are degraded according to whether matrix or fiber damage is predicted such as:

$$\int \sigma_i d(\varepsilon_i l_c) = G_{ic} \tag{5}$$

where $G_{ic}$ is the fracture toughness of the fiber and matrix materials.



a. T700/X4201 coupon b. T700/X4201 pipe

**Figure 7.** FE models of the filament wound coupon and pipe under bending

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## 4. Results and Conclusions

The predicted stress-strain response of the T700/X4201 coupons is shown in Fig. 8 which correlates well with the experimental results. The predicted damages patterns of the corresponding pipe under bending are shown in Fig. 9. The intended work shows examples of damage prediction by the proposed progressive damage models which take into account different failure modes of the pipe undergoing tension, compression or bending. In addition, nonlinearity in the stress-strain responses can be also well captured by the damage models, considering the mechanical property degradation of composites before its ultimate failure. This requires a series of coupon tests in principal directions of composite materials should be done to measure different nonlinear shear or tension responses. When coupled with cohesive elements for delamination modeling, the progressive modeling framework is capable of estimating both intralaminar and interlaminar damage of composite risers.

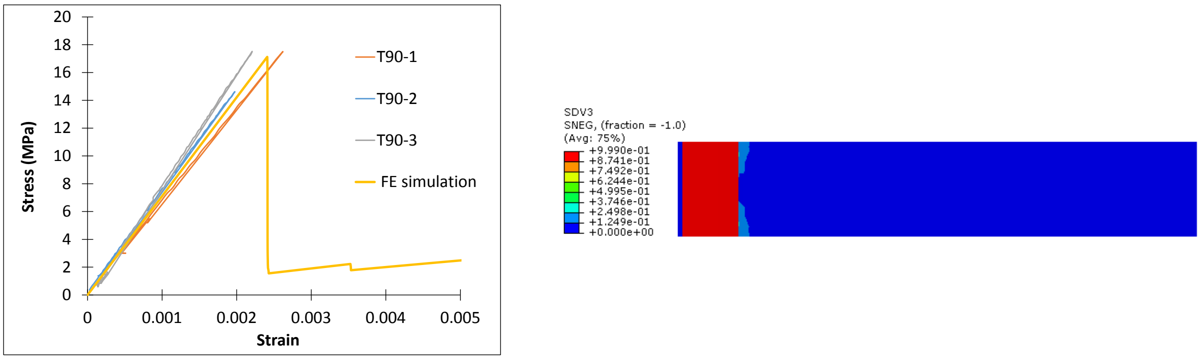

**Figure 8.** Predicted stress-strain curves and damage of the $[90]_{56}$ coupons

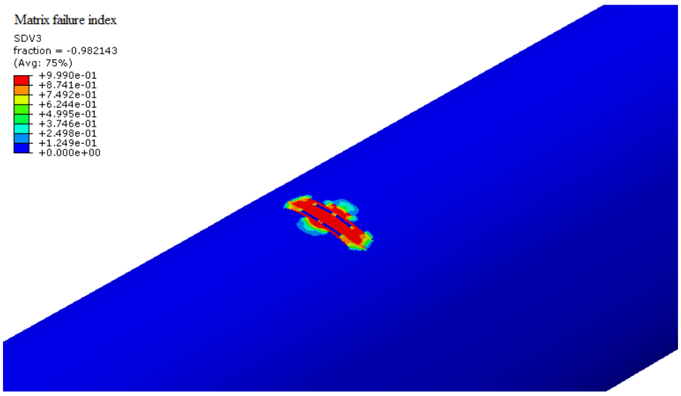

**Figure 9.** Predicted failure of the $[90]_{56}$ pipe under bending

In summary, bending responses of two-meter filament would Toray T700/X4201 pipe with different composite laminates are experimentally and numerically studied. We started with simple pipe layup configurations such as the $[90]_{56}$ and $[45/-45]_{28}$ laminates to analyze the bending responses of the composite pipes as well as to examine the tension and shear responses of filament wound composites extracted from the composite pipes. The current work is being further extended to bending analyses of complicated pipe layups such as the $[90/15/-15/90/45/-45/45/-45/45/-45]_5$+$[45/-45]_3$ pipe with inclusion of a metallic inner liner serving as environmental protection for composite risers.

## 5. Acknowledgement

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