An experimental investigation of properties of Q345 steel pipe at elevated temperatures

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Abstract

This paper presents the results of an extensive experimental investigation of the thermal and mechanical properties of Q345 steel pipe at elevated temperatures using both the steady-state and transient-state test methods. Under these two test conditions, the thermal expansion coefficient, yield strength and elastic modulus of the specimens at different temperatures were measured. The tested results indicate that both the yield strength and elastic modulus decrease gradually with increasing temperature. However, at the same temperature, both the yield strength and elastic modulus tested using the steady-state test are higher than those tested using the transient-state test. Hence, it is less safe to use the material properties tested using the steady-state test for fire resistance design of the steel structure. Based on the transient-state test results, the models of the mechanical properties of Q345 steel pipe at elevated temperatures were proposed. These models can be used for the design and analysis of Q345 steel pipe structures under fire conditions.

Keywords: Q345 steel pipe; High temperature; Steady-state test; Transient-state test; Mechanical properties; Fire resistant design

Highlights:

- To generate the thermal and mechanical properties of Q345 steel pipe at elevated temperatures using both the steady-state and transient-state test methods.
- To compare the material properties tested using both the steady-state and the transient-state tests.
- To propose the models of thermal and mechanical properties of Q345 steel pipe at elevated temperatures.

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1. Introduction

With advantages such as higher torsional rigidity and no weak axis under flexural condition, steel pipes have been widely used in the construction of steel structures, especially in the long-span structures such as: hangars, exhibition halls and sports stadiums. The use of steel pipes can achieve a combination of lightweight structure with good architectural aesthetic. However, it is well known that steel structures have relative poor fire-resistance. Hence, it is important to do the fire resistance design for the steel structures. At present, performance-based fire resistance design approach became more popular, in which advance computer modelling is an essential. The accuracy of the computer modelling is largely depended on the accurate material properties used. Therefore the study of mechanical properties of steel pipe at elevated temperatures is very important to make sure that the fire-resistance design of steel pipe can be done properly.

In recent years, based on the material properties generated from the research on the thermal and mechanical properties of steel at elevated temperatures, a number of code's specifications for fire-resistant design have been developed [1-4]. Outinen et al. [5] proposed a fire-resistant design model based on the high-temperature transient-state test results of rod tensile specimen made of S355 structural steel. Makelainen et al. [6] studied the high-temperature mechanical properties of the rod tensile specimen made of S420M structural steel using the transient-state test, and proposed a constitutive model for fire-resistant design of S420M steel at different temperatures. Li et al. [7] used the steady-state test to determine the mechanical properties of Q345 steel under high-temperature and provided the corresponding stress-strain relationships. Thereafter, Outinen et al. [8-10] investigated the high-temperature mechanical properties of steel of different grades using the steady-state test. Based on the tested results they proposed a material model for fire resistant design of S355 and S420M steel products. Chen et al. [11-13] studied the high-temperature properties of stainless steel, high-strength structural steel and cold-formed structural steel using the steady-state and the transient-state test methods, and provided the corresponding stress-strain relationships. Gunduz and Acarer [14] investigated the effect of heat treatment on high-temperature mechanical properties of low-alloy medium-carbon steel. Young [15] conducted a study on the high-temperature bearing properties of high-strength stainless steel using the steady-state test and numerical simulation. Kodur et al. [16] summarised the research results on high-temperature mechanical properties of steel and identified the differences between the results. Based on the results of the steady-state and the transient-state tests, Chen Wei and Ye [17] analysed the high-temperature mechanical properties of G550 high-strength cold forming steel and found that there are large differences among tested results using different test methods. The maximum difference was even more than 50%. Xuhong et al. [18, 19] investigated the deterioration law of the mechanical properties of S460 high-strength structural steel under a transient fire environment, and proposed suggestions for fire resistant of S460N, HSS 460N, S460M and other steel products. Sultan et al. [20] carried out a study on the tensile deformation performance of G92 high-strength structural steel under high temperature. Sinaie et al. [21, 22] studied the high-temperature mechanical properties of crude structural steel under a repetitive loading, and proposed the corresponding correlation of stress-strain-temperature. Xue et al. [23] took advantage of the existing models to develop a finite element simulation for analysing the creep limit of P91 steel pipe with weakened pipe walls, and proposed the relationships and methods for safety assessment of the structures.

Based on the preceding literature review, however, it is evident that the most of the experimental studies at elevated temperatures are on the section steel or cold-formed steel. To the authors' knowledge, the experimental studies on the high-temperature mechanical properties of steel pipe specimen are very limited. In addition, many existing fire-resistant specifications for steel structure and experimental studies on high-temperature properties of steel material are mainly based on the steady-state test method. At present, Q345 steel pipe has been widely used in the construction industry in China. To our knowledge, no research has been carried out on the material properties of Q345 steel pipe at high temperature by using transient-state test method. For steel structures under fire conditions the stress-strain relationship is better represented by using transient test method. Previous research indicated that considerable difference of test results of high temperature properties of steel materials exists between the steady-state test and transient-state test conditions.

Therefore, it is needed to conduct a research on the high temperature properties of Q345 steel pipe based on transient-state test method. The main objectives of this paper are:

- To conduct a series of well control testes on Q345 steel pipe at elevated temperatures for generating their thermal and mechanical properties at elevated temperatures using both the steady-state and transient-state test methods.
- To compare the material properties tested using both the steady-state and transient-state tests.
- To propose the models of mechanical properties of Q345 steel pipe at elevated temperatures which can be used for fire resistance design of the Q345 steel pipe structures.

2. Experimental study

2.1 Test method

In this study the tests were divided into three groups: A, B and C. Group A was the thermal expansion test. Group B was the tests using the steady-state test method. Group C was the tests using the transient-state test method. As mentioned in Section 1, Q345 steel pipe is mainly used in the long-span structures such as: hangars, exhibition halls and sports stadiums. Hence, those structures have long-span and greater height from the ground with large space. Under fire conditions the temperature increase rate in the steel pipe is therefore relatively slower than those in conventional buildings. Hence, in this study the heating rate of 20℃/min was adopted for all tests. According to previous studies [18, 19], when steel temperature > 600℃, the loss of yield strength in high-strength structural steel generally reaches 60-70%. Further, the loss of yield strength of cold forming steel generally exceeds 90% [13, 17]. Hence, in this study steel temperature of 600 °C was chosen as the maximum testing temperature.

(1) Thermal expansion test (Group A)

In the loaded specimen tested at elevated temperatures, using high temperature MTS 632.54F-11 *extensometers*, total strain ε_{total} was measured. The stress-related strain ε_{σ} can be calculated by subtracting thermal strain ε_T from the total strain ε_{total}. Therefore, in this study, the thermal expansion tests were first conducted by measuring the thermal expansion values of the specimen at different temperatures.

The thermal expansion tests were conducted under no loading condition. Firstly, one end of the specimen was fixed while the other end was kept free. Then, the temperature was increased from room temperature (25℃) to 600 ℃ at an increasing rate of 20℃/min. While the temperature was rising, the specimen was elongated freely, so the thermal strain values at different temperature can be measured. Group A includes three specimens (A1, A2, A3), and the average result of the thermal strains was taken as the thermal strain at each temperature level.

(2) Steady-state test (Group B)

In the steady-state tests 7 temperatures (25℃, 100℃, 200℃, 300℃, 400℃, 500℃ and 600℃) were used including ambient temperature. For the ambient temperature test, the load increased at a constant strain rate of 0.001/min. The yield strength and the elastic modulus at room temperature were measured. For the high temperature tests, the temperature of specimen increased from room temperature to the required temperature at a rate of 20℃/min under no-loading condition. After that, the specimen was kept at that constant temperature for 20 min. Then the specimen was loaded with strain rate of 0.001/min, and the yield strength and elastic modulus of the specimen were measured. Previous research indicated that the test results were affected by the loading strain rate used. However, the loading strain rate of 0.001/min is recommended in the Chinese Standard (GB/T 4338-2006). Hence, it was adopted in this research. The test at each temperature was repeated three times and the averaged value was used. A total of 21 specimens were tested in this study.

(3) Transient-state test (Group C)

In the transient-state tests, six stress levels of the specimens were used. They are: $0.1f_y$, $0.2f_y$, $0.4f_y$, $0.6f_y$, $08f_y$ and $1.0\ f_y$, where f_y (=356 MPa) is the yield strength at ambient temperature. During the transient-state test, the specimen was loaded with a loading rate of 0.05 *kN/s* to the required load level (determined from required stress level of the specimen). Then the load was kept constant and the specimen was heated continuously at a rate of 20℃/min. During the test the total strain of the specimen was measured at different temperatures. The test at each loading condition was repeated three times and the averaged value was used. A total of 18 specimens were tested.

2.2 Test equipment

In this research, the loading rig of MTS810 material testing machine (as shown in Fig. 1) was used. For the heating, the high-temperature environment chamber (see Fig. 2) with a temperature controller (see Fig. 3) was used. The controller can control the accuracy of the temperature to ± 1 ℃. The heating chamber was commercially supplied by Changchun Mechanical Engineering Research Institute.

2.3 Test specimens

In this study, all the specimens were extracted from the same-batch of Q345 steel pipe with a diameter of 102 mm and a wall thickness of 5 mm. The position where the specimens were extracted is shown in Fig. 4. The dimensions of the specimen are shown in Fig. 5, and a photograph of the specimens is shown in Fig. 6. Table 1 gives the chemical composition of Q345 steel. At room temperature, the tensile yield strength of the specimen f_y = 356 MPa.

3. Result and analysis

3.1 Thermal expansion coefficient

Fig. 7 shows the thermal strains of three tested specimens of Q345 steel pipe in Group A against temperature. As shown in the figure, the thermal strain of the specimen increases with increasing temperature. When temperature < 200℃, the increasing rate of thermal strain is relatively low. After temperature > 200℃, the increasing rate of thermal strain is higher. Table 2 shows the averaged thermal expansion coefficients of Q345 steel pipe at different temperatures.

3.2 Analysis of steady-state test results

Fig. 8 shows the tested stress-strain relationships at different temperature levels for Group B (steady-state test). In this study, the stress with a 0.2% strain was used as the nominal yield strength of the specimen. The reduction factor of yield strength is then defined as the ratio of yield strength of steel f_{yT} at temperature T to the yield strength f_y at room temperature. Further, the ratio of the stress and strain within the strain range of 0.01-0.1% was chosen for the evaluation of the elastic modulus. The reduction factor of the elastic modulus is defined as the ratio of the elastic modulus, E_T, at temperature T and the elastic modulus at room temperature, E. Tables 3 and 4 show the average yield strength, average elastic modulus and the corresponding reduction factors, f_{yT}/f_y and E_T/E.

It can be seen from Table 3 and Fig. 8 that the yield strength of Q345 steel decreases with the increase in temperature T. When T < 200 ℃, the yield strength f_{yT} are higher than 90% of f_y at the room temperature. When T > 300 ℃, the reduction of the yield strength f_{yT} increases gradually. In particular, when T > 500℃, the yield strength f_{yT} reduces sharply. At T = 600 ℃, the yield strength f_{yT} = 170 MPa, which is 48% of the yield strength f_y = 356 MPa at room temperature.

As shown in Fig. 8 and Table 4, same as the yield strength, the elastic modulus E_T of Q345 steel decreases with the increase in temperature T. When T < 300 ℃, there is no significant reduction of the elastic modulus E_T. At 300℃, $E_T = 1.86\times10^5$ MPa which is 92% of the elastic modulus $E = 2.03\times10^5$ MPa at room temperature. However, when T > 300 ℃, the reduction of the elastic modulus E_T increases considerably. At T = 600 ℃, the elastic modulus $E_T = 1.36\times10^5$ MPa, which is only 67% of the elastic modulus E at room temperature.

3.3 Analysis of transient-state test results

In the transient-state test, only the total strain ε_{total} of each specimen under a certain stress level at elevated temperatures was measured. The stress-strain relationship could not be measured directly. The yield strength and elastic modulus also could not be measured directly. However, based on the measured total strain ε_{total} and thermal strain ε_T, the stress-related strain ε_σ can be calculated by subtracting the thermal strain ε_T from the total strain ε_{total}. Hence, the relationships of the stress-related strain ε_σ and temperature under different load levels can be generated. Fig. 9 shows the stress-related strain ε_σ against temperature under different load levels for the Group C tests. During the transient-state test, the ultimate temperature T_u for each test is the maximum temperature that specimen could withstand.

As can be seen from Fig. 9, the ultimate temperature T_u of Q345 steel pipe specimen reduces with increasing stress level. At $\sigma = 0.1f_y$, the ultimate temperature T_u > 700℃; at $\sigma = 0.6 f_y$, the ultimate temperature T_u < 600°C; and at $\sigma = 1.0\ f_y$, the ultimate T_u < 500°C. At a high stress level the strain increases rapidly with increasing temperature, when the temperature of the specimen reached to the ultimate temperature T_u then the specimen was finally ruptured.

In order to determine the stress-strain curves at different temperatures for the transient-state tests the following procedure was used. First, the measured total strain ε_{total} at a certain stress level σ and temperature T was selected. Then, the thermal strain ε_T at that temperature was subtracted from the total strain ε_{total} to give the stress-related strain ε_σ then a point (ε_σ, σ) of the stress-strain curve at that temperature was identified. To repeat the same procedure, the stress-strain curve at that temperature was generated. Through this approach, the stress-strain relationships of Q345 steel pipe at different temperatures (under transient-state test condition) can be obtained, as shown in Fig.10.

Similar to the results obtained from the steady-state test, the stress corresponding to 0.2% residual strain was defined as the nominal yield strength f_{yT}. Within the stress range of 0.1-0.4f_y, the ratio of stress and stress-related strain was chosen as the elastic modulus E_T. Thus, Tables 5 and 6 show the yield strength, the elastic modulus and the reduction factors, f_{yT}/f_y and E_T/E.

As can be seen from Table 5, the yield strength of Q345 steel pipe measured using the transient-state test declines with increasing temperature. When T > 500°C, the decline rate of the yield strength is faster. At T = 600°C, the yield strength f_{yT} = 140 MPa, which is only 39% of the yield strength at room temperature. The measured elastic modulus also decreases with increasing temperature. When T > 300°C, the decline rate of the yield strength is faster. At T = 600°C, the elastic modulus $E_T = 1.2\times10^5$ MPa, which is only 59% of the elastic modulus at room temperature.

3.4 Comparative analysis of steady-state and transient-sate test results

Fig. 11 shows the comparisons of stress-strain relationships at different temperatures by using the steady-state and transient-state tests. As can be seen from Fig. 11, the measured stress-strain relationships of Q345 steel pipe using the steady-state and the transient tests are different, and the differences vary at different temperatures. The differences on the stress-strain relationships caused by the different test methods can be explained from the deformation of steel specimen under load and temperature conditions. For the deformation of steel at high-temperature, the effects of stress, temperature and time should be taken into account concurrently.

For steel structures in fire the coupling effect of stress, temperature and time requires special consideration. In the steady-state test, the specimen is heated up to a certain temperature without stress. Then the heated specimen is kept at a constant temperature for a certain period. During this period, only thermal strain occurs within the specimen. Then the specimen with the constant temperature is loaded to failure. During the loading stage, both temperature and stress existed. Hence, at this stage, both stress-related strain and coupling strain, resulted from the combine effect of stress, temperature and time, are generated. Due to the short-duration of the loading stage, the coupling strain generated in the steady-state test is very small and could be neglected. However, in the transient-state test, the specimen is loaded first. Then the specimen is heated continuously at constant stress until the failure of specimen is reached. Hence, during the heating stage the specimen is under the combined effect of stress, temperature and time. This effect results the coupling strain generated within the tested specimen. Normally, compared to the steady-state test the heating time required for the transient-state test is considerable long. Therefore, the coupling strain generated during the test is relatively large and cannot be ignored. It is obviously that the material properties tested using the transient-state test method are more closed to real condition of steel structures under fire conditions. The differences between the stress-strain relationships produced from two test methods are mainly due to the coupling strain generated by combined effect of temperature, stress and time. The magnitude of the coupling strain is influenced by the factors, such as temperature, stress and time.

As shown in Fig. 11, it is evident that high stress and high temperature will generate more significant coupling strain which has more impact on the measured material properties. Figs 12 and 13 show the variations of the yield strength and the elastic modulus with temperature for two test methods. As can be seen from Fig.12, at T = 100 ℃, the yield strengths measured by the two methods are almost identical. But, at T = 600 ℃, the yield strength measured by the steady-state test is 21% higher than the one measured by the transient-state test. This is mainly due to the effect of creep of steel at elevated temperature. For the steady-state test the test time was about 2 to 3 min, therefore the creep effect is negligible. However, for the transient-state test it took 30 min to reach

600 ℃. Hence, the creep of steel may have considerable influence on the test results. Further research is needed before the general conclusion can be drawn.

As shown in Fig. 13, the influence of the test method on high-temperature elastic modulus is only significant when T > 300℃. For T = 400 ℃, 500 ℃ and 600 ℃, the elastic modulus measured by the steady-state test are 13.73%, 20.15% and 13.33% higher than those measured by the transient-state test, respectively. It can be seen that the reductions of the modulus of elasticity for both steady-state and transient-state tests are nonlinearly changed with temperature. Previous research [24] also demonstrated this complex steel property at elevated temperature. This is mainly due to the complex interactions between temperature, stress, heating rate and steel material structures. Further research is needed before the general conclusion can be generated.

3.5 Comparison of test results with existing material models

As mentioned in Section 3.4 at high temperature (T > 300℃), the yield strength and elastic modulus measured by the transient-state test are both lower than those measured by the steady-state test. Therefore, it is reasonable to use the material properties tested by the transient-state test method for the fire resistance design of Q345 steel pipe structures. Hence, in this study, based on the transient-state test results the three polynomial model developed by Li et al [7] was adopted to calibrate with the test data using numerical analysis software Origin. Based on this procedure, two simplified formulas (equations (1) and (2)) were proposed to calculate the reduction factors of the yield strength and elastic modulus of Q345 steel pipe at elevated temperatures. Fig. 14 shows the comparison between the test results and the model's predictions. It is evident that predictions from the proposed models are in good agreement with the test data.

$$f_{yT}/f_y = -7.36\times10^{-9}T^3+5.195\times10^{-6}T^2-0.00145T+0.98689 \qquad (100℃\leq T\leq600℃) \qquad (1)$$

$$E_T/E=2.155\times10^{-11}T^4-2.53\times10^{-8}T^3+8.70\times10^{-6}T^2-0.0016T+1.0829 \qquad (100℃\leq T\leq600℃) \qquad (2)$$

The comparisons between the proposed models and some existing material models from the current design codes and research literatures for calculating the yield strength and elastic modulus are presented Figs. 15 and 16.

As can be seen from Fig. 15, the reduction factors of the yield strength at elevated temperatures, calculated using different models are considerable vary. Compared to the current model the reduction factors of the yield strengths at high temperature calculated using the ECCS model [4] and model proposed by Li et al. [7] are relatively lower. On the other hand, the reduction factor of the yield strengths at high temperature calculated using Eurocode 3[1] is considerable higher than the values predicted by the current model. Hence, all previous models mentioned above are not suitable for fire resistance design of Q345 steel pipe structures. The model proposed in this study gives a medium values compared to the other models. So, the current model can be used for the fire resistance calculations of Q345 steel pipe structures.

As shown in Fig. 16, the reduction factors of the elastic modulus at higher temperature calculated using different models are considerable vary as well. It is evident that Eurocode 3 model [1] gives lower reduction factor and Li et al. model [7] has higher reduction factor. Again, the model proposed in this study gives a medium values compared to the other models. From this comparative analysis, it is clear that since the production standards and material properties of steel are different in different countries. Also the test methods and analysis are different as well. Therefore, for fire resistant design of steel structures the material models should be selected carefully.

4. Conclusions

This paper presents the results of an extensive experimental investigation of the thermal and mechanical properties of Q345 steel pipe at elevated temperatures using both the steady-state and transient-state test methods. Under these two test conditions, the thermal expansion coefficient, the yield strength and elastic modulus of the specimens at different temperature were measured. Based on the transient-state test results, the models of mechanical properties of Q345 steel pipe at elevated temperatures were proposed. The predictions of proposed models were compared with the calculations using some existing models from the current design codes and research literatures. Based on the results generated in this research, some conclusions can be drawn as the following:

- The test results indicate that both the yield strength and elastic modulus of Q345 steel pipe decrease gradually with increasing temperature. However, at the same temperature, both the yield strength and elastic modulus tested using the steady-state test are higher than those tested using the transient-state test.

- At T = 600℃, the yield strength measured by the steady-state test is 21% higher than the one measured by the transient-state test. For T = 400℃, 500℃ and 600℃, the elastic modulus measured by the steady test are 13.73%, 20.15% and 13.33% higher than those measured by the transient-state test, respectively.
- Based on the results of transient-state test, two models were proposed to calculate the reduction factors of the yield strength and elastic modulus of Q345 steel pipe at elevated temperatures. These models can be used for the design and analysis of Q345 steel pipe structure under fire conditions.
- From the comparison of current models' predictions with the calculations generated using some existing material models from the current design codes and research literatures, it is evident that all previous models mentioned in this study are not suitable for the fire resistance design of Q345 steel pipe structures.
- From this study, it is clear that since the production standards and material properties of steel are different in different countries. Also the test methods and analysis are different as well. Therefore, for fire resistant design of steel structures the material models should be selected carefully.

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List of Tables and Figures

Table 1 Chemical compositions of Q345 steel (%)

C	Si	Mn	P	S	Cr	Ni	Cu	Mo	Al	V	Sn
0.18	0.26	1.48	0.024	0.008	0.021	0.007	0.010	0.003	0.020	-	-

Table 2 Thermal expansion coefficients of Q345 steel at different temperatures

Temperature	100℃	200℃	300℃	400℃	500℃	600℃
Thermal expansion coefficient （10^{-5}/℃）	0.454	0.781	1.009	1.105	1.135	1.153

Table 3 Yield strength and its reduction factor of Q345 steel (steady-state test)

Temperature (℃)	25	100	200	300	400	500	600
Yield strength (MPa)	356	321	321	312	283	249	170
Reduction factor (f_{yT}/f_y)	1.000	0.903	0.903	0.877	0.796	0.701	0.478

Table 4 Elastic modulus and its reduction factor of Q345 steel (steady-state test)

Temperature (℃)	25	100	200	300	400	500	600
Elastic modulus ($\times 10^5$MPa)	2.03	1.94	1.88	1.86	1.74	1.61	1.36
Reduction factor (E_T/E)	1.000	0.959	0.928	0.916	0.859	0.793	0.671

Table 5 Yield strength and its reduction factor of Q345 steel (transient-state test)

Temperature (℃)	25	100	200	300	400	500	600
Yield strength (MPa)	356	315	302	295	266	234	140
Reduction factor (f_{yT}/f_y)	1.000	0.885	0.848	0.829	0.747	0.657	0.393

Table 6 Elastic modulus and its reduction factor of Q345 steel (transient-state test)

Temperature (℃)	25	100	200	300	400	500	600
Elastic modulus ($\times 10^5$MPa)	2.03	2.01	1.90	1.83	1.53	1.34	1.20
Reduction factor (E_T/E)	1.000	0.990	0.936	0.901	0.754	0.660	0.591

Fig. 1　MTS810 material testing machine

Fig. 2　High-temperature environment chamber

Fig. 3　Temperature controller for the environment chamber

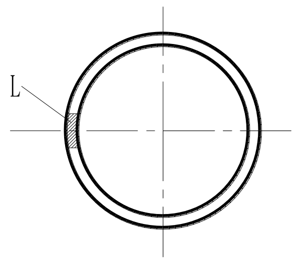


Fig. 4　Extraction position of specimens within the steel pipe

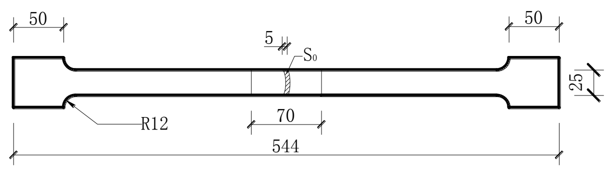


Fig. 5　Detailed dimensions of the specimens (all in mm)

Fig. 6　A photograph of specimens

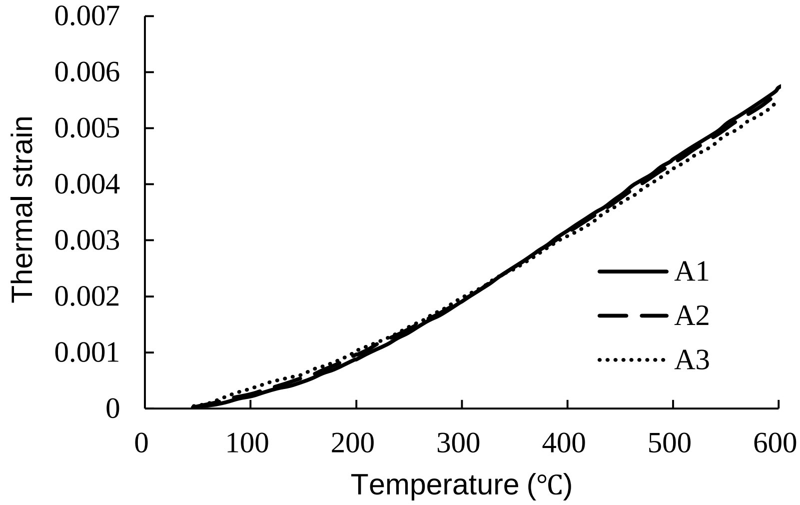


Fig.7 Thermal strains of three specimens of Q345 steel pipe at elevated temperatures

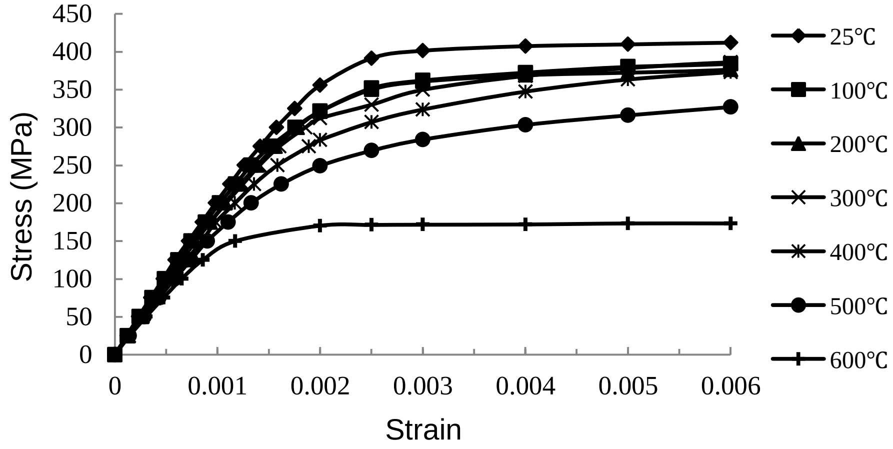


Fig. 8 Stress-strain curves of Q345 steel pipe at different temperatures (Steady-state test)

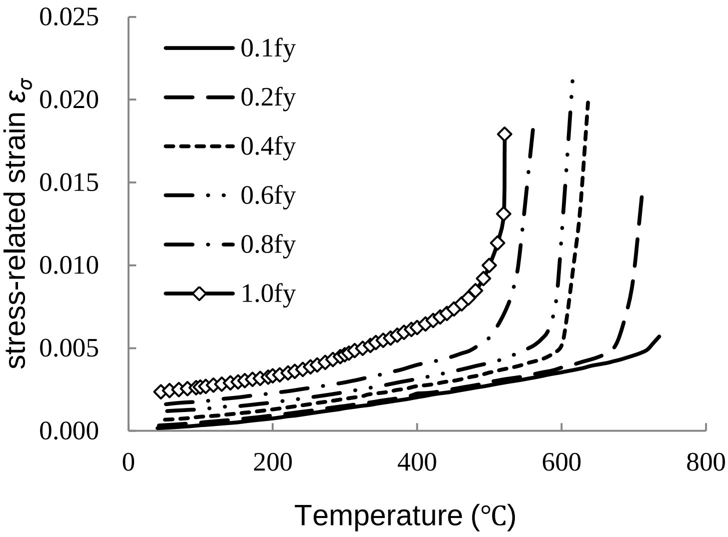


Fig. 9 Stress-related strain ε_σ of Q345 steel pipe against temperature at different stress levels (Transient-state test)

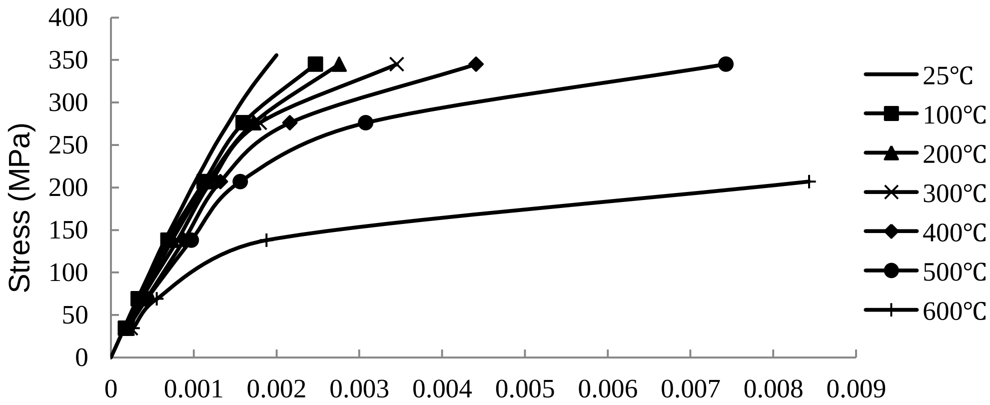
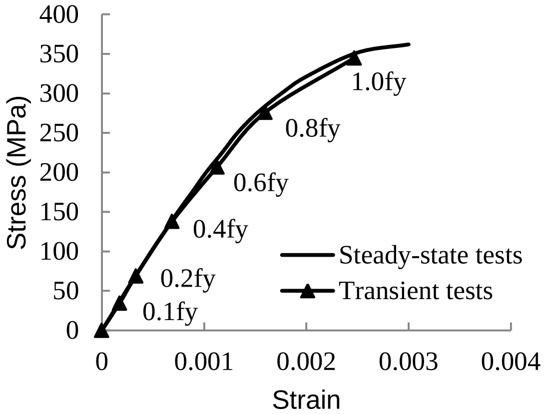
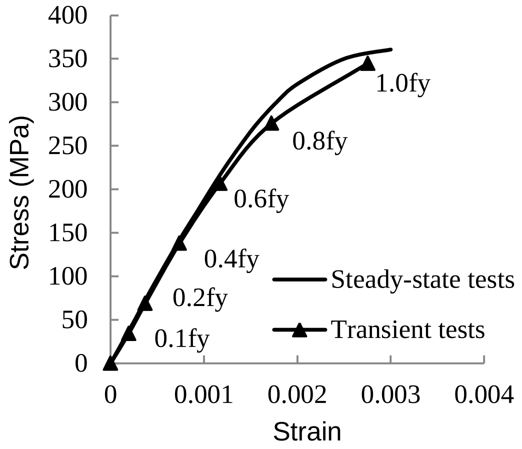


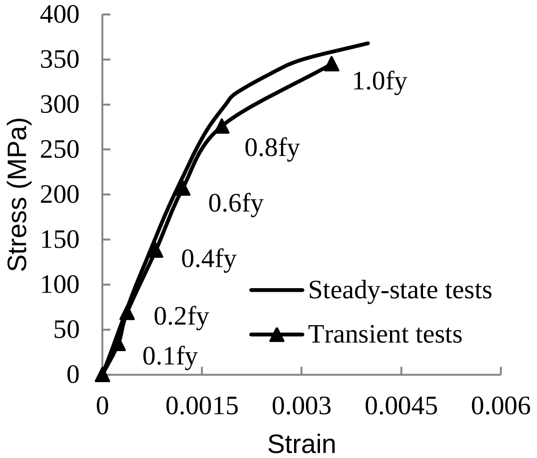
Fig. 10 Stress-strain curves of Q345 steel pipe at different temperatures (Transient-state test)



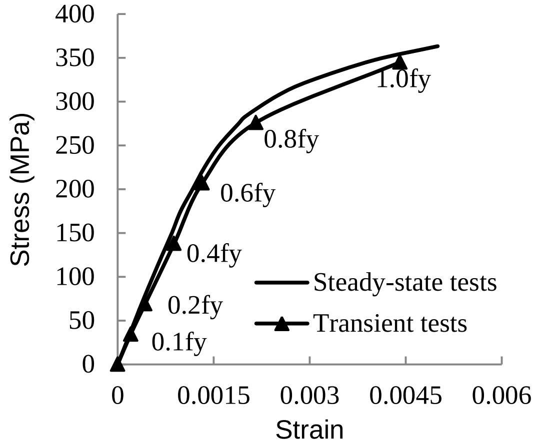
(a) 100 ℃



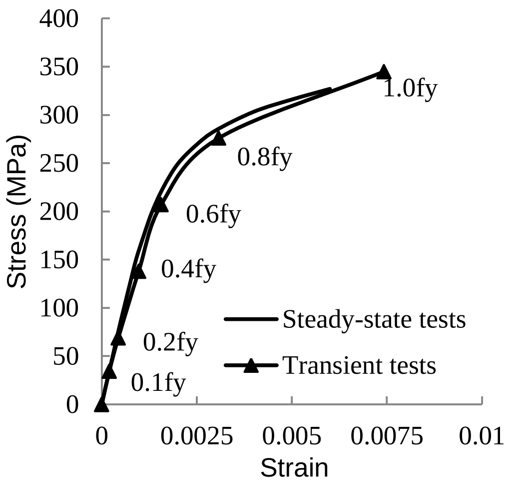
(b) 200 ℃



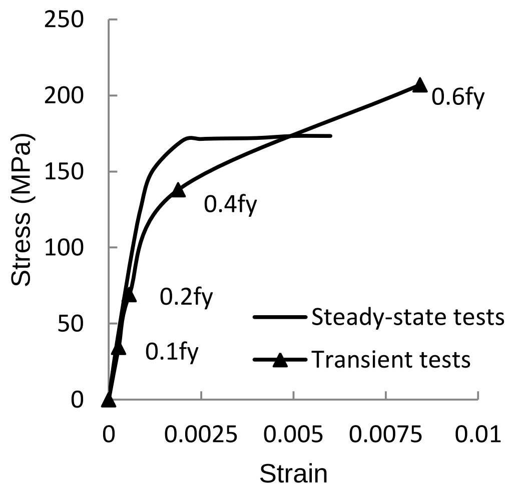
(c) 300℃



(d) 400℃



(e) 500℃



(f) 600℃

Fig. 11. Comparison of stress-strain relationships of Q345 steel pipe at different temperatures for both steady and transient state tests

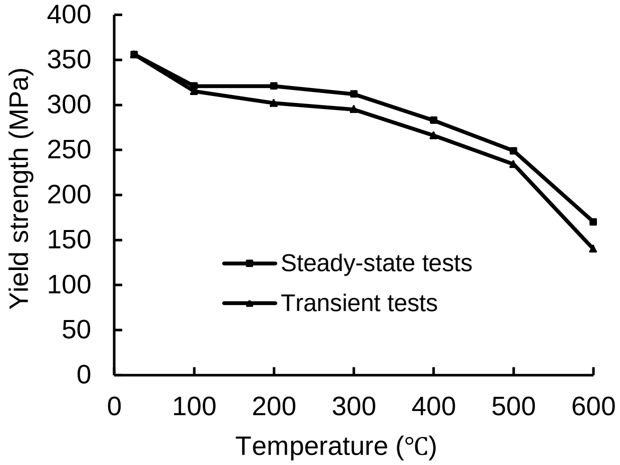


Fig. 12 Comparison of yield strengths measured using the two test methods

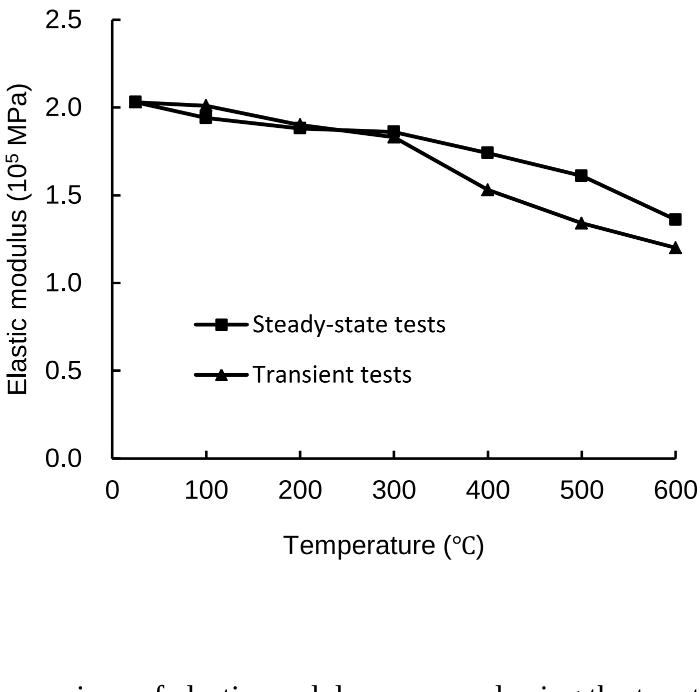


Fig. 13 Comparison of elastic modulus measured using the two test methods

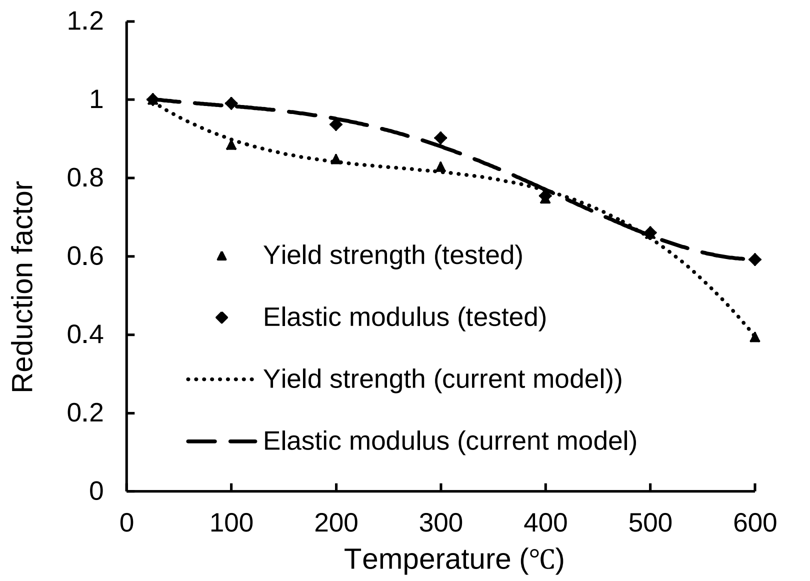


Fig. 14 Comparison between testes results and proposed models

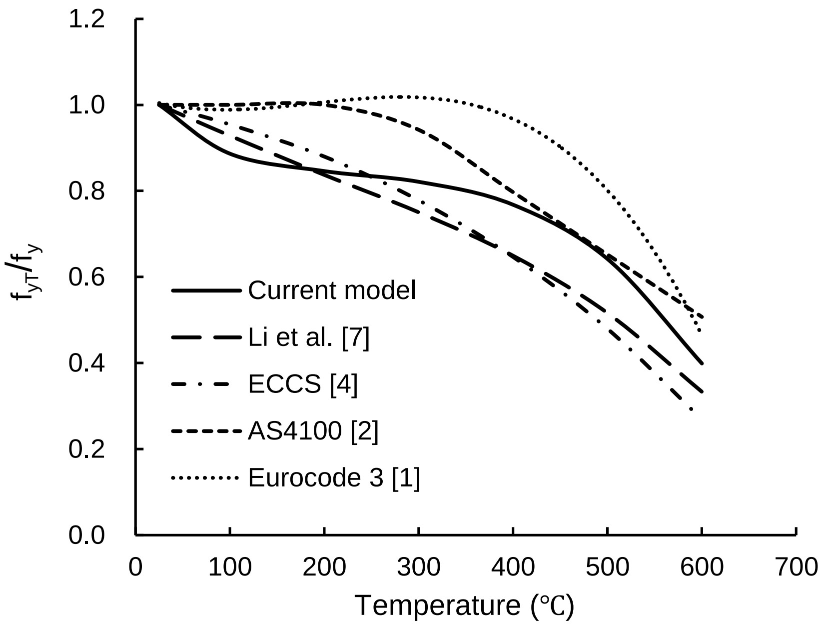


Fig. 15 Comparison of yield strength and temperature relationships from different models

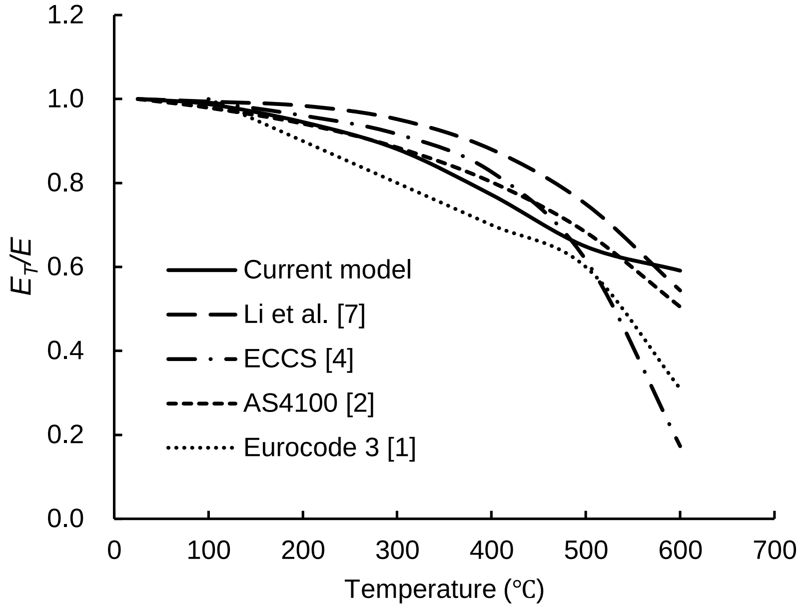


Fig. 16 Comparison of elastic modulus and temperature relationships from different models