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Structural stability of fire-resistant steel (FR490) H-section columns at elevated temperatures

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Abstract. A fundamental limitation of steel structures is the decrease in their load-bearing capacity at high temperatures in fire situations such that structural members may require some additional treatment for fire resistance. In this regard, this paper evaluates the structural stability of fire-resistant steel, introduced in the late 1999s, through tensile coupon tests and proposes some experimental equations for the yield stress, the elastic modulus, and specific heat. The surface temperature, deflection, and maximum stress of fire-resistant steel H-section columns were calculated using their own mechanical and thermal properties. According to a comparison of mechanical properties between fire-resistant steel and Eurocode 3, the former outperformed the latter, and based on a comparison of structural performance between fire-resistant steel and ordinary structural steel of equivalent mechanical properties at room temperature, the former had greater structural stability than the latter through 900°C.

Keywords: fire-resistant steel; FR490 steel; mechanical property; thermal property; stability; structural performance

1. Introduction

A fire in an office or residential building can claim not only people's lives but also serious property damage. Unfortunately, however, the number and severity of fires have increased steadily. One major reason for this is the increase in the building's fire load (Zalok *et al*. 2009). Since structural steel is not fire-resistant, fire-resistant materials are additionally required for steel-framed buildings to satisfy fire regulations. However, fire-resistant materials applied to the surface of structural steel members such as columns and beams have two serious limitations. First, protective materials can be separated from the surface of steel members when the temperature increases rapidly, and second, the coarse and irregular surface of structural members caused by the application is not aesthetically pleasing. These limitations have been main drivers of the development of high-performance fire-resistant steel in Korea. Fire-resistant steel, FR490 has the same mechanical properties such as the yield stress and the elastic modulus at room temperature as

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structural steel SM490 (Kwon 1997).

Previous studies have examined the properties of fire-resistant steel at high temperatures but focused mainly on the comparison of mechanical properties between fire resistant steel and ordinary structural steel (Sakumoto *et al*. 1994, Kelly and Sha 1999). Recently, Yang *et al*. (2006) and Chung *et al*. (2010) tested fire-resistant steel by considering behaviors of columns, beams, and beam-columns at high temperatures, and Muratov *et al*. (2007) provided a new approach to developing new types of highly efficient fire-resistant steel.

There are two ways to evaluate the fire resistance of new types of structural steel. One way is the full-scale fire test using a furnace based on the standard fire curve approved by national authorities. The other is the calculation method using mechanical properties, thermal data at high temperatures, and the magnitude of the fire (Kwon and Kwon 2012). The full-scale fire test is more reliable, but because it requires substantial amounts of time and money, it is becoming less popular. The calculation method is a reasonable alternative in evaluating the efficiency of fire-resistant materials because it can better provide an appropriate solution than the costly full-scale fire test. Therefore many countries have adopted the calculation method as the primary method for evaluating the fire resistance of buildings since 1990s. In recent years, an increasing number of studies on the modeling the structures to predict their fire resistance was conducted (Yu *et al*. 2008, Usmani *et al*. 2009, Kodur *et al*. 2010, Somaini *et al*. 2012). However, few studies have evaluated the structural stability of fires-resistant steel at high temperatures.

This paper employs tensile coupon tests to assess the structural behavior of the FR490 H-section columns at high temperatures and proposes an empirical model of mechanical and thermal properties. The test results are compared with the properties defined in the Eurocode 3 (1995), and the heat transfer analysis and stress analysis were conducted using data derived at high temperatures to evaluate the structural stability of FR490 H-section columns. The structural stability of FR490 H-section columns at high temperatures is compared with SM490 H-section columns of equivalent mechanical properties.

2. Test programs for determining mechanical and thermal properties at high temperatures

Recently, accumulated knowledge of fire science and engineering has led to a new field in building design, namely fire engineering design. The engineering method can provide better safety, greater construction efficiency, and higher degrees of freedom for buildings than the prescription method from the design perspective.

To accurately predict the structural behavior of structural steel members and frames at high temperatures, the strength of the fire in the fire cell and basic information on mechanical and thermal properties are required. In this paper, the tensile coupon tests summarized in Table 1 were employed to obtain data on the mechanical and thermal properties of FR490. As shown in the table, the measuring temperature was initially 20°C and then was increased in increments of 100°C from 100°C to 900°C to evaluate the mechanical properties at different temperatures. Three tensile specimens were prepared for each measuring temperature for reliability.

2.1 Mechanical properties

FR490 is a fire-resistant steel defined in the Korean Standard (KS D 3865), and its major chemical components and mechanical properties are summarized in Table 2.

Table 1 Tensile coupon test scheme

Steel grade	Measuring temperatures (°C)		Number of specimens
FR490	Room temperature	20	30 (3 × 10)
	High temperature	100-900 (ΔT = 100)	

Table 2 Chemical components and mechanical properties

Steel grade	Components (%)							Mechanical properties			
	C	Si	Mn	P	S	Cr	Mo	Thickness (mm)	Yield stress (MPa)	Tensile stress (MPa)	Elongation (%)
FR490	0.08	0.37	0.13	0.015	0.002	0.29	0.31	$16 \geq t$	325	490~610	17
								$16 < t \leq 40$	315		21
								$t > 40$	295		23

Table 3 Test speed and temperature tolerance

Temperature	Ram speed		Temperature tolerance
	Until yield point	After yield point	
Room temperature	17.0 MPa . sec	20.0%/min	–
High temperature	7.0 MPa . sec	7.5%/min	300~600°C = ± 3°C 600~900°C = ± 4°C

Fig. 1 Test configuration

The specimens for the tensile test were cut from the raw plate in the rolling direction. KS D 0802 (2003) and KS D 0026 (2002) were employed in the tensile coupon test at room temperature and high temperatures, respectively. The tensile tests were conducted using a universal testing machine equipped with a furnace which can be heated up to 900°C. The loading starts immediately after the surface temperature of specimen reaches the desired temperature. The test configuration is shown in Fig. 1.

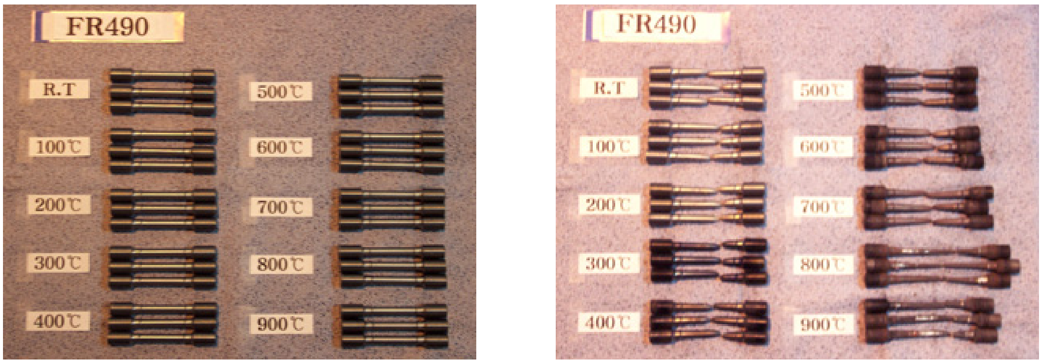

Fig. 2 Test specimens (before and after)

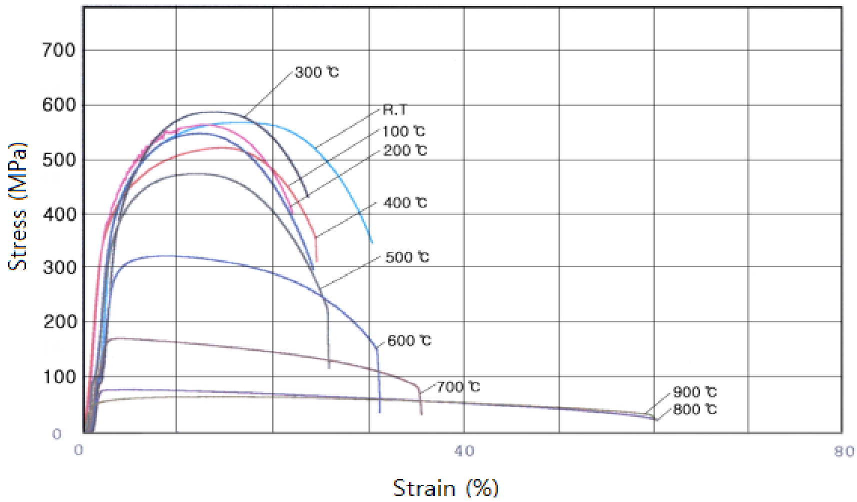

Fig. 3 Stress-strain relations

Test conditions for the tensile coupon test are summarized in the Table 3, and the specimen shapes before and after the test are shown in the Fig. 2, respectively.

Fig. 3 shows the results of the tensile coupon test, and Table 4 shows the average values for the yield stress, the ultimate tensile stress, the elastic modulus, and elongation. Since the yield plateau was not clear on the stress versus strain curves for some specimens at high temperatures, the 0.2% offset stress and the 0.5% extension under load yield strength were applied to determine the yield stress of the specimens. As shown in Fig. 2, the yield and tensile stress decreased, and there was an increase in elongation according to the increase in the temperature except for 300°C and 400°C. The elastic modulus also decreased according to the increase in the temperature except for 200°C, and there was a significant decrease at 700°C. There was a sharp increase in elongation after 700°C, and the yield and tensile strength decreased sharply between 500°C and 600°C. The 0.2% offset yield stress at 500°C was 88.0% of that at room temperature, and tensile strength was 83.4%. The yield and tensile strength decreased sharply between 500°C and 600°C, and the 0.2% offset yield stress at 600°C was 72.8% of that at room temperature. Tensile strength was 56.8 %.

Table 4 Test results for mechanical properties

Temperature (°C)	Yield strength (MPa)		Tensile strength (MPa)	Elastic modulus (MPa)	Elongation (%)
	0.2% offset	1.0% extension			
20	352.90	436.15	571.07	200333.75	30.22
100	319.48	391.40	522.67	195385.99	26.15
200	341.95	424.51	569.45	229917.69	22.43
300	340.90	435.40	586.31	160813.10	23.87
400	314.50	413.33	543.32	150363.83	24.57
500	310.61	389.74	476.37	158749.46	24.85
600	256.79	300.85	324.21	122952.05	31.66
700	152.96	167.84	168.34	112557.1	33.15
800	75.93	79.60	80.35	77518.73	58.07
900	49.01	57.43	68.27	37189.59	58.31

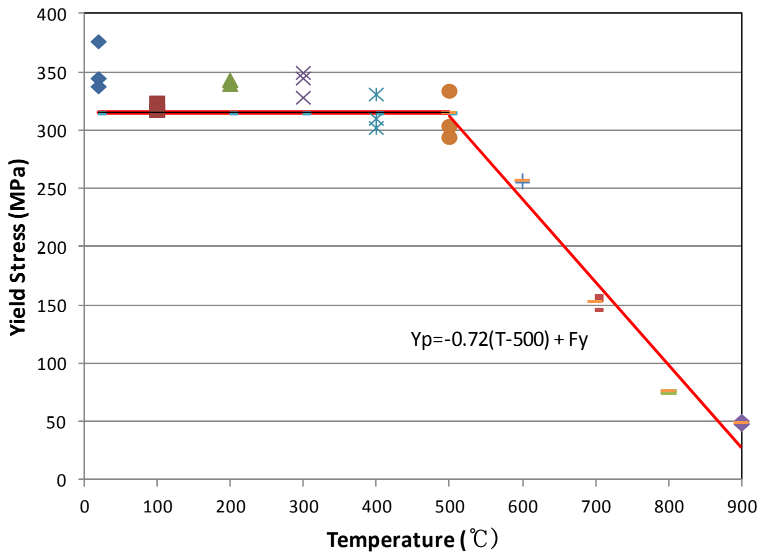

Fig. 4 0.2% proof stress-temperature curve

Fig. 3 shows the relationship between the 0.2% offset strength and temperature. As shown in the figure, the yield stress remained at the same level as that measured at room temperature until 500°C but decreased sharply afterward. Based on these test results, simple equations for the yield stress can be given by

for $T \leq 500$°C

$$Y_p = F_y \tag{1a}$$

for $T > 500$°C

$$Y_p = -0.72(T - 500) + F_y \tag{1b}$$

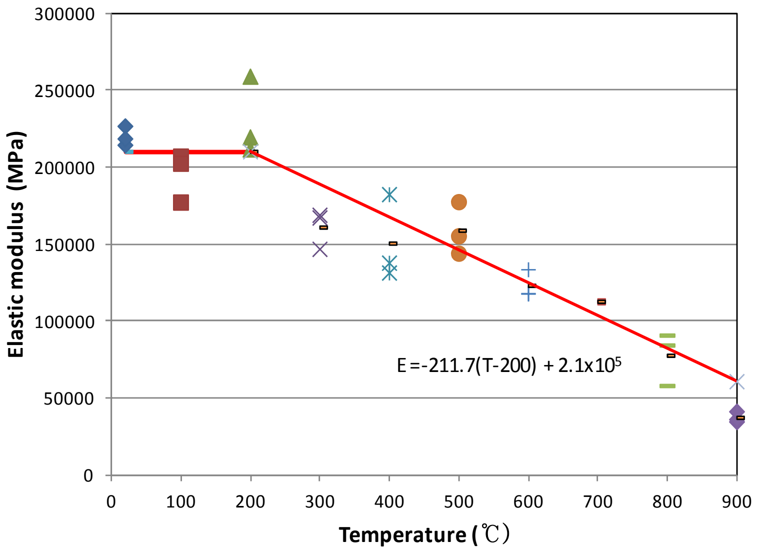

Fig. 5 Elastic modulus-temperature relations

where T is the temperature and F_y is the nominal yield stress.

Fig. 4 compares the proposed equations for the yield stress with the test results and shows the accuracy of the yield stress predicted by Eqs. (1a) and (1b). The coefficient of determination (R^2) for the equation was 0.97.

Fig. 5 shows the elastic modulus obtained at high temperatures. The elastic modulus showed a constant value until 200°C and then declined steadily up to 900°C. Simple formula for the elastic modulus E can be proposed as

for $T \leq 200°\text{C}$

$$E = 2.1 \times 10^5 \quad \text{(MPa)} \tag{2a}$$

for $T > 200°\text{C}$

$$E = -211.7(T - 200) + 2.1 \times 10^5 \quad \text{(MPa)} \tag{2b}$$

The comparison of test results and the elastic modulus predicted by Eqs. (2a) and (2b) in Fig. 4 confirms the reliability of the formulae proposed for the elastic modulus. The coefficient of determination (R^2) for the formula was 0.92.

In Korea, since there lacks a sufficient data-base for the mechanical properties of structural steel at high temperatures, and therefore the structural stability of members or frames have been conducted using the databases from Eurocode 3. Although the Eurocode 3 databases are limited to ordinary structural steel, they are generally accepted to be useful. Therefore, for the validation of FR490 data, the relationship between the reduction ratio of the test yield stress and temperature was compared with that for Eurocode 3. As shown in Fig. 6, the yield stress of FR490 showed a smaller decrease with an increase in temperature until 900°C than that of Eurocode 3. The yield stress of ordinary structural steel and FR490 was constant until 400°C and 500°C, respectively, but they showed a similar pattern of decreases in the yield stress with an increase in temperature. This indicates that FR490 showed greater structural stability than ordinary structural steel defined in

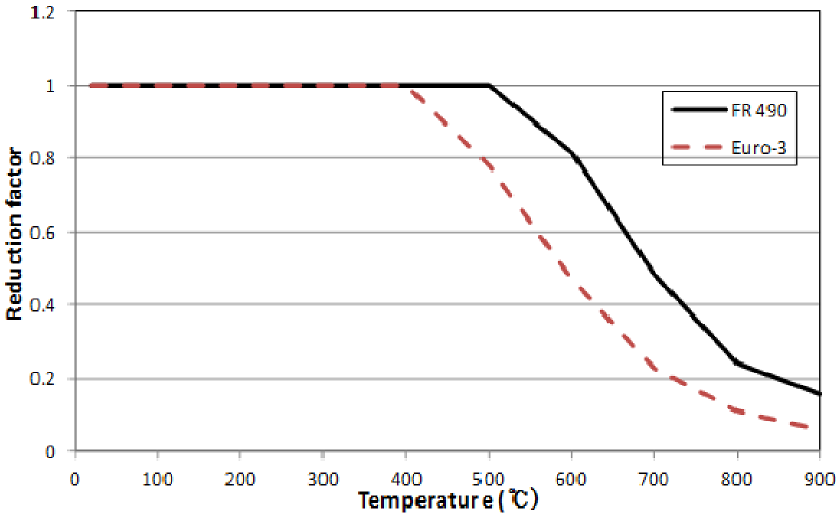

Fig. 6 Comparison of the yield stress reduction factor

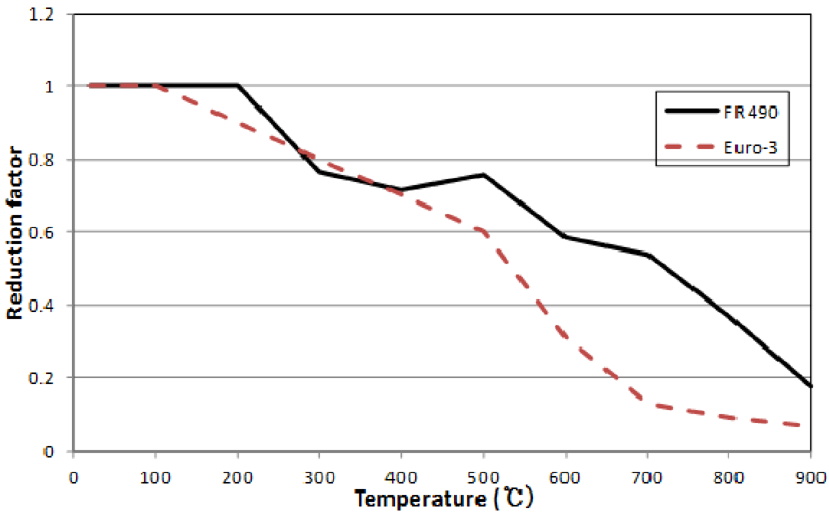

Fig. 7 Comparison of the elastic modulus reduction factor

Eurocode 3 under fire conditions.

In general, an increase in temperature reduced the elastic modulus of structural steel. The reduction factor for the elastic modulus of FR490 according to an increase in temperature was compared with that for ordinary structural steel in Eurocode 3 in Fig. 6. As shown in Fig. 7, the elastic modulus of FR490 generally showed values greater than or equal to those for ordinary structural steel defined in Eurocode 3 based on an increase in temperature up to 900°C

Based on the comparison of the yield stress and elastic modulus in Figs. 5 and 6, which had significant effects on structural stability, the mechanical properties of FR490 were different from those of Eurocode 3 at high temperatures. Therefore, these mechanical properties should be used

Table 5 Test scheme for thermal properties

Steel grade	Test conditions	
	Measuring temperature	Number of specimen
FR490	From room temperature to 1,000°C at an interval of 100°C	3 per each measuring temperature

directly in evaluating the structural stability of FR490 steel members, but when there are no available data on other types of fire-resistant steel, mechanical properties of ordinary structural steel can be used in a conservative manner instead of those of other types of fire-resistant steel.

2.2 Thermal properties

Exact values for the thermal expansion, specific heat, and thermal conductivity of structural steel should be used for the accurate prediction of structural behaviors at high temperatures in fire situations. In particular, exact values for heat expansion represent a crucial factor in the calculation of the secondary stress based on the expansion or shrinkage of each frame member. As shown in Table 5, a series of test was designed to investigate the thermal expansion, specific heat, and thermal conductivity of FR490.

The test results for thermal expansion of FR490 are compared with the provision in Eurocode 3 in Fig. 7. FR490 expanded nonlinearly up to 700°C. This tendency was slightly different from that for Eurocode 3. More specifically, the expansion of FR490 was greater than that of ordinary structural steel in Eurocode 3 from room temperature to 850°C. However, their expansion at 850°C was equal. As shown in Fig. 8, the expansion and secondary stress of FR490 may exceed those of ordinary structural steel defined in Eurocode 3.

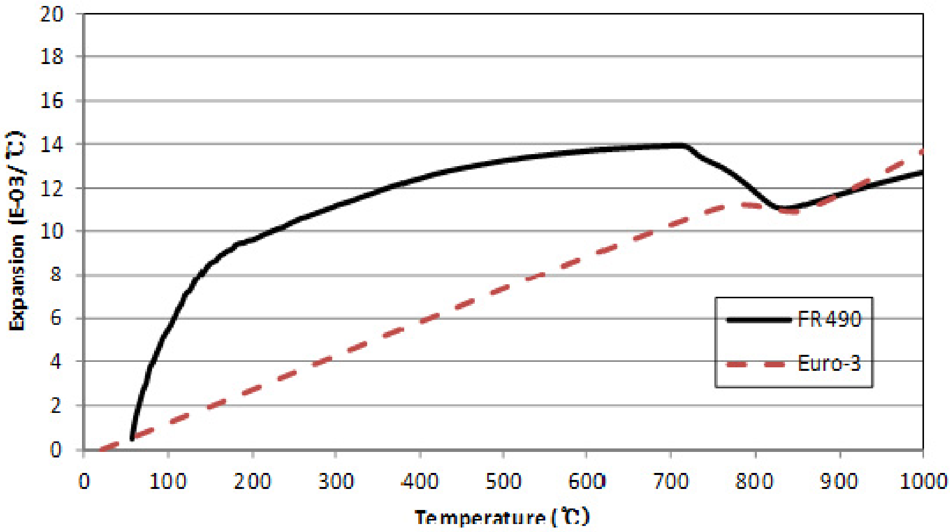

Fig. 8 Comparison of the linear expansion at high temperatures

Table 6 Thermal properties of FR490 steel

Temperature (°C)	Thermal diffusion coefficient a (m^2/s)	Specific heat C_p (J/kgK)	Thermal conductivity k (w/m·K)	Density ρ (kg/m^3)
20	0.11E-04	452.7	39.627	7750
112	0.11E-04	460.7	37.959	
197	0.10E-04	503.9	38.578	
302	0.09E-04	547.1	37.758	
400	0.08E-04	600.9	36.942	
503	0.07E-04	677.0	35.839	
605	0.06E-04	796.3	34.237	
706	0.04E-04	1407.1	43.002	
805	0.05E-04	1137.2	45.183	
900	0.06E-04	991.3	47.870	

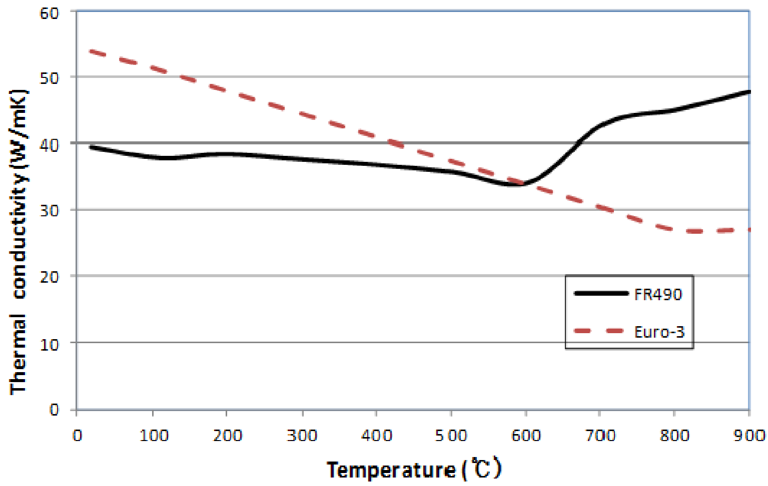

Fig. 9 Comparison of thermal conductivity at high temperatures

Specific heat and the thermal diffusion coefficient were measured to calculate the thermal conductivity of FR490 steel. The thermal properties of FR490 measured at high temperatures are summarized in Table 6. Thermal conductivity was calculated using the following equation

$$k = a \cdot \rho \cdot C_p \tag{3}$$

where

k : Thermal conductivity (W/m·K)
a : Thermal diffusion coefficient (m^2/s)
ρ : Density (kg/m^3)
C_p : Specific heat (J/kgK).

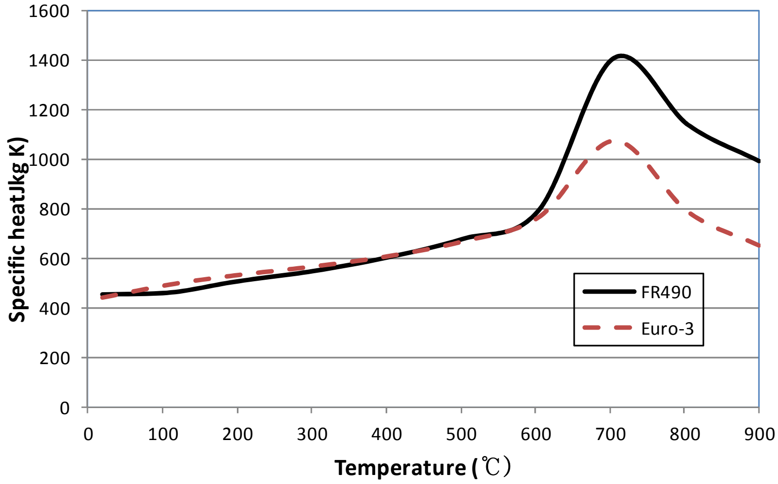

Fig. 10 Comparison of specific heat at high temperatures

The thermal conductivity of FR490 calculated using Eq. (3) is compared with that of Eurocode 3 in Fig. 9. As shown in Fig. 9, the thermal conductivity of FR490 decreased slightly up to 600°C and was slightly lower than that of Eurocode 3. After 600°C, however, the thermal conductivity of FR490 increased slightly, unlike in the case of Eurocode 3. Eurocode 3 showed a linear decrease up to 800°C and then showed a constant value up to 900°C. Based on the comparison between FR490 and Eurocode 3 in Fig. 9, FR490 underwent a smaller temperature increase than that defined in Eurocode 3 up to 600°C. This suggests that the calculated thermal conductivity can be used effectively to predict the exact increase in the temperature of FR490 in fire situations. Comparison between specific heat of FR490 and that of Eurocode 3 is shown in Fig. 10. As shown in Fig. 10, the specific heat of FR490 is quite similar to that of Eurocode 3 up to 600°C. However, in the temperature range from 600°C to 900°C, the specific heat of FR490 is significantly higher than that of Eurocode 3.

3. Simulation of the structural stability of H-section columns at high temperatures

3.1 Test section geometry and axial load

It is crucial for buildings with structural steel frames to not only have sufficient fire resistance but also be pleasing in appearance. Therefore, fire engineering methods for fire-resistant steel have been used frequently in recent years as a reasonable design alternative in New Zealand and other countries. In addition, fire-resistant steel framed buildings with no additional fire-resistant materials have been found to be economically and aesthetically competitive.

The welded H-300 × 300 × 10 × 15 section column shown in Fig. 11 was made of FR490 steel plates and was tested to failure at high temperatures to evaluate structural stability under fire situations. The overall column length was 3,500 mm, and both end boundary conditions were hinges to allow for flexural buckling in a single half-wave about the minor axis.

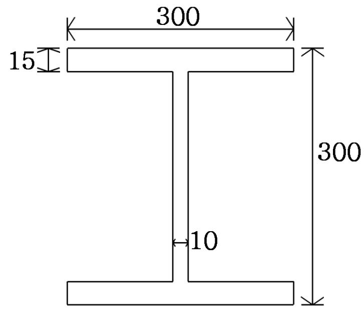

Fig. 11 H-300 × 300 × 10 × 15 section (unit: mm)

The heating of the H-section column produced its extension, local buckling, and overall buckling. However, since the width-to-thickness ratios for the web and flanges of the test H-section column were 9.67 and 27.0, respectively, which were too low to allow the occurrence of elastic local buckling before overall buckling, flexural buckling about the minor axis governed the buckling behavior. Therefore, the governing equation for the column can be given as

$$F_{cr} = \left(1 - 0.4\frac{\lambda}{\lambda_{pt}}\right)^2 F_{yt} \tag{4}$$

where

λ : Slenderness ratio $(= \frac{l_k}{i})$,
l_k : Column length,
i : Minimum radius of gyration,
λ_{pt} : Limiting slenderness ratio $(= \sqrt{\frac{\pi^2 E_t}{F_{yt}}})$,
F_{yt} : Yield stress at high temperatures.

The maximum load was determined by the allowable stress multiplied by the cross-sectional area of the H-section column, as given by Eq. (5a), and the applied load for the calculation was estimated as 1,450.0 kN, which was 60% of the maximum load

$$P_c = f_c A, \tag{5a}$$

where

$$f_c = \frac{F_{cr}}{S.F} = \frac{\left(1 - 0.4\left(\frac{\lambda}{\lambda_{pt}}\right)^2\right) \cdot F_{yt}}{\frac{3}{2} + \frac{2}{3}\left(\frac{\lambda}{\lambda_{pt}}\right)^2} \tag{5b}$$

and A is gross cross sectional area.

3.2 Numerical simulation

To evaluate the fire resistance of the H-section column, fire sources such as the standard or natural fire curve should be determined first, and then the surface temperature and deflection should be calculated. The known mechanical and thermal properties were used to calculate the surface temperature and deflection of the section. There are many computer programs for calculating the surface temperature and deflection of structural members, including ABAQUS and ANSYS. In this paper, STA-FR (structural analysis program for fire resistance), developed for the calculation of the surface temperature, defection, and maximum stress of steel structures, was used (Kwon 2009). There are many fire sources which are easily available and useful, and among those, the standard fire curve defined in the Korean Standard KS F 2257-7 (2005) was adopted.

3.2.1 Surface temperature

To calculate the surface temperature of the H-section column, the following equation was used with the heat transfer coefficient of 23 (W/m^2°C) and the resultant emissivity of 0.5 (SBI 1976)

$$\alpha = 23 + \frac{5.77\varepsilon_r}{\theta_t - \theta_s}\left[\left(\frac{\theta_t + 273}{100}\right)^4 - \left(\frac{\theta_s + 273}{100}\right)^4\right](W / m^2\,°C) \tag{6}$$

where

α : Surface coefficient of the heat transfer,
θ_t : Gas temperature of the inner furnace (KSF 2257-1),
θ_s : Surface temperature of the H-section,
ε_r : Resultant emissivity.

Simple equations for the specific heat of FR490 steel by temperature are summarized in Table 7. Table 8 shows a similar set of equations for the specific heat of SM490 for comparison purposes.

Table 7 Specific heat equations for FR490 steel

Temperature	Specific heat (J/gK)	Coefficient of determination (R^2)
$T \le 600$°C	$0.0006T + 0.40$	0.94
600°C < $T \le 700$°C	$0.006T - 2.86$	1.00
700°C < T	$0.002T + 2.90$	0.98

Table 8 Specific heat equations for SM490 steel

Temperature	Specific heat (J/gK)	Coefficient of determination (R^2)
$T \le 500$°C	$0.008T + 0.38$	0.94
500°C < $T \le 710$°C	$0.0061T - 2.78$	1.00
710°C < $T \le 810$°C	$-0.0035T + 3.97$	1.00
810°C < T	$0.0007T + 0.62$	1.00

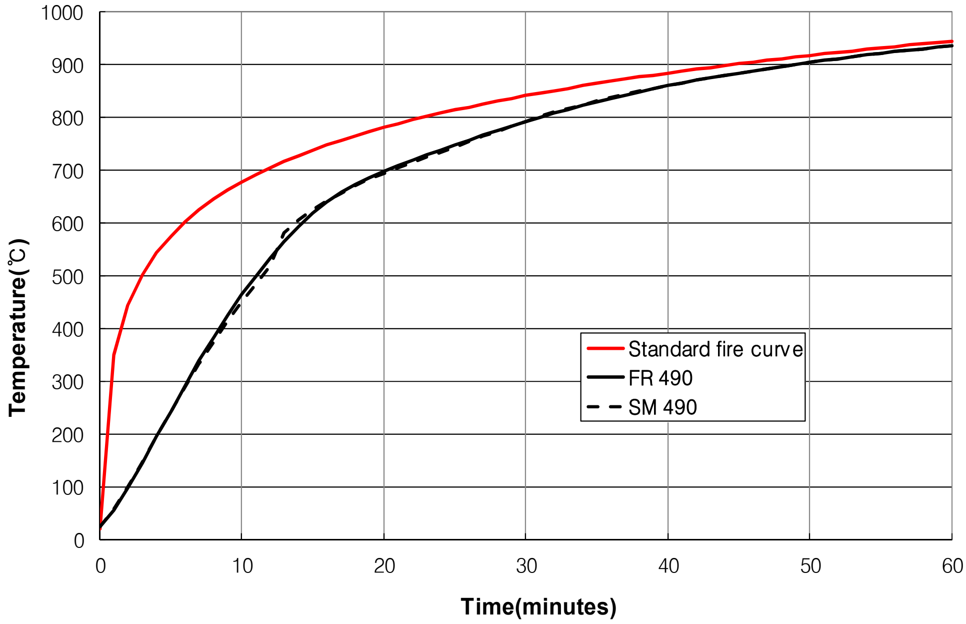

Fig. 12 Surface temperature-elapsed time curves

The surface temperature vs. time curves for the FR490 steel H-section column obtained by STA-FR were shown in Fig. 12. As shown in Fig. 10, the surface temperature of the H-section column increased rapidly and approached the standard fire curve after 40 minutes. For the comparison of patterns of increases in the surface temperature of the FR490 H-section column, Fig. 8 shows the curve of the surface temperature vs. time for the SM490 column of equivalent mechanical properties at room temperature. There was little difference in the surface temperature between the two H-section columns, but the surface temperature of the SM490 H-section column continued to be slightly higher from early stage to 60 minutes.

3.2.2 Deflection

The heat-stress analysis was conducted to evaluate the structural stability of H-section columns at high temperatures. The analysis assumed no change in the cross section of the column and calculated the total linear expansion of the column by the direct sum of the shortened length caused by the applied compressive load and the extended length from the increase in temperature. The elastic shortening of the column was determined using Hook's law as follows

$$\Delta\ell = P_\theta L_\theta / E_\theta A, \tag{7}$$

where

Δl : Shortened length (mm),
P_θ : Axial load at the highest temperature (N).
L_θ : Column length (mm),
E_θ : Elastic modulus at high temperatures (MPa),
A : Cross-sectional area (mm^2).

Table 9 Extension rate equations for FR490 at high temperatures

Temperature	Specific heat (J/gK)	Coefficient of determination (R^2)
$T \leq 150°C$	$0.0813T - 3.07$	0.97
$150°C < T \leq 720°C$	$-0.0093T + 8.16$	0.93
$720°C < T \leq 750°C$	$-0.028T + 34.37$	1.00
$750°C < T$	$0.0094T + 3.28$	0.99

The linear extension of columns varied mainly according to the temperature range. The extension rate was employed as a function of temperature. The extended length of the FR490 steel column was calculated using the simple equations in Table 9. Table 10 shows a similar set of equations for the linear extension rate for SM490 steel for comparison purposes.

The axial deflection of the H-section column was a result of the difference between the linear extension from the increase in temperature and the contraction from the axial compressive load, which was up to 60% of the maximum load capacity. Fig. 11 shows the relationship between the axial deflection and time for the FR490 steel column. The deflection increased for 21 minutes and then decreased rapidly to 26 minutes, after which it remained constant to 60 minutes. There was little difference between FR490 and SM490 steel section. The deflection of FR490 section did not change from 26 minutes to 60 minutes, but that of SM490 decreased steadily. Based on the comparison of deflections between the FR490 and SM490 H-section columns in Fig. 13, FR490 section column sustained the axial load longer than SM490section column under fire situations.

3.2.3 Maximum stress

The change in the axial stress due to increase of surface temperature for the FR490 H-section column was investigated to study the structural performance at high temperatures. Fig. 12 shows the relationship between the maximum stress and the surface temperature for the FR490 H-section column. As shown in Fig. 12, the maximum stress decreased steadily until approximately at 700°C and then dropped sharply, indicating that the FR490 H-section column safely sustained the applied load until about 700°C. Fig. 14 also shows the curve of the maximum stress versus temperature relations for the SM490 H-section column for comparison purposes. The two columns showed a similar decreasing until 550°C, an allowable temperature for ordinary structural steel defined in the Korean Standard. With an increase in temperature beyond this point, the maximum stress decreased sharply until 900°C. Based on the comparison of the maximum stress between the FR490 and SM490 H-section columns, FR490 column showed better structural performance at high temperatures than ordinary structural steel (SM490) column until 700°C.

Table 10 Extension rate equations for SM490 at high temperatures

Temperature	Specific heat (J/gK)	Coefficient of determination (R^2)
$T \leq 150°C$	$0.0789T - 2.40$	0.98
$150°C < T \leq 730°C$	$0.0099T + 7.99$	0.93
$730°C < T \leq 860°C$	$-0.00224T + 30.57$	0.96
$860°C < T$	$0.0088T + 3.55$	0.99

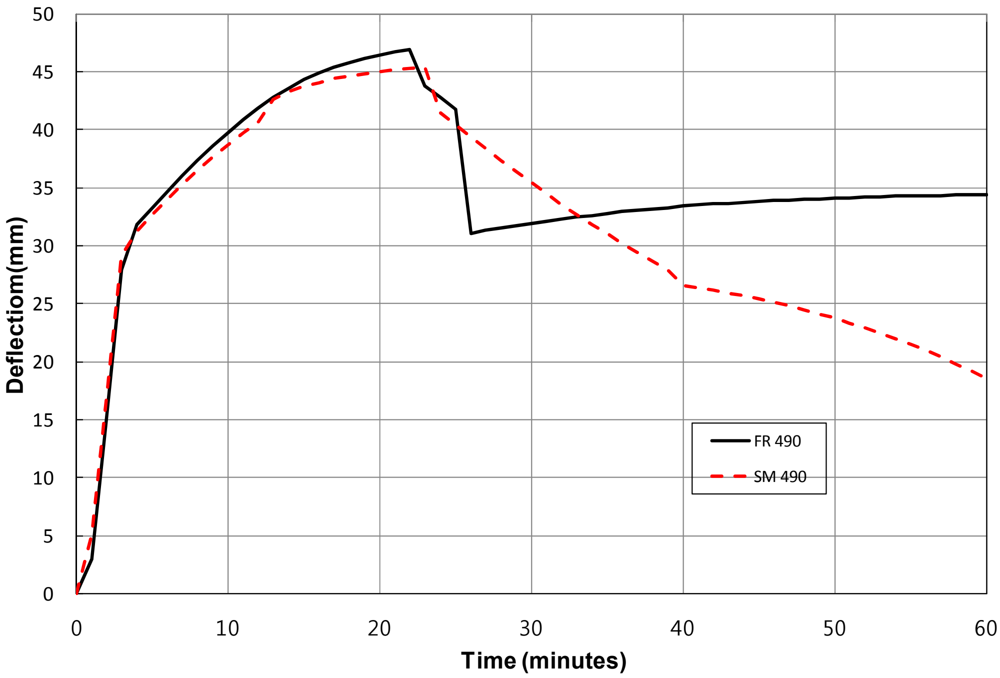

Fig. 13 Axial deflection-elapsed time relations under a standard fire curve

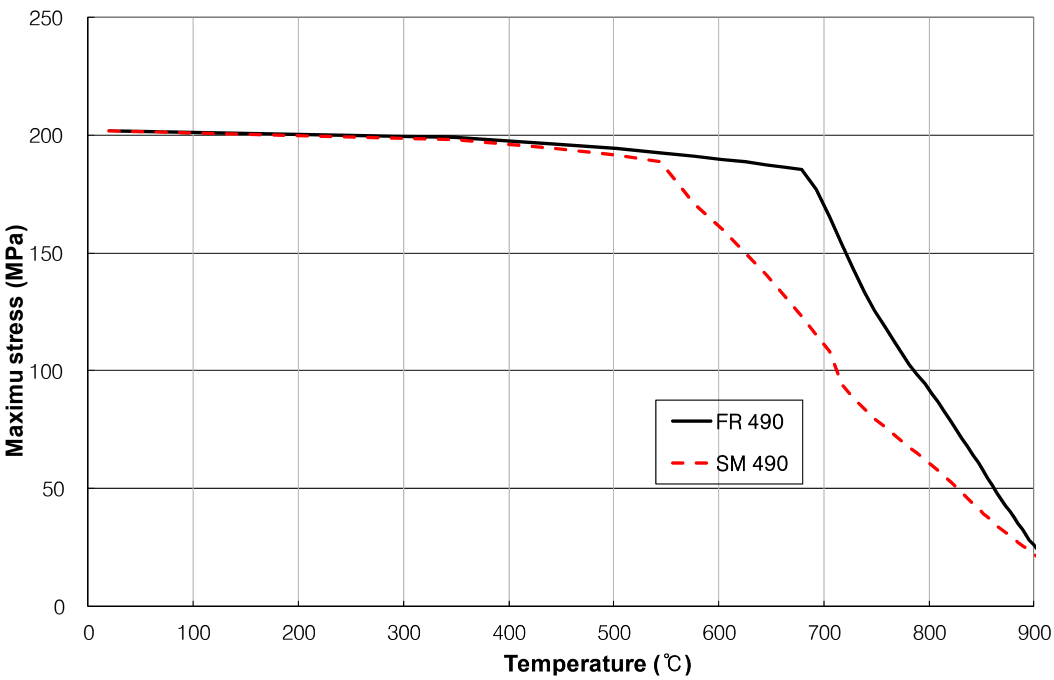

Fig. 14 Maximum stress-temperature relations under a standard fire curve

4. Conclusions

To evaluate the structural stability of fire resistant steel (FR490) H-section column, tensile coupon tests were conducted at high temperatures. In addition, the heat transfer and stress were analyzed for the FR490 H-section column, and the results were compared with those for ordinary structural steel, namely the SM490 H-section column. The mechanical and thermal properties of FR490 were determined at high temperatures, and simple equations for the yield stress, elastic modulus, specific heat, and extension rate were derived for FR490 steel. The yield stress and elastic modulus of FR490 at high temperatures were more robust than those defined in Eurocode 3. This suggests that the evaluation of the structural stability of fire-resistant steel structures should use their own mechanical and thermal properties to more accurately predict the behavior of members and frames. The surface temperature of the FR490 H-section column showed the same rising pattern as that of the SM490 column, but the deflection of FR490 column was smaller than that of SM490 column. The maximum stress was constant until 700°C for FR490 H-section column, whereas it was until 550°C for SM490. This suggests that FR490 steel columns are superior to ordinary structural steel columns in terms of structural stability at high temperatures. Fire-resistant steel can better improve the fire resistance of steel structures than ordinary structural steel and thus reduce the need for additional fire-resistant materials.

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