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RESIDUAL STRENGTH OF STRUCTURAL STEELS: SN400, SM520 AND SM570

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Abstract
This paper presents post-fire mechanical properties of mild to high-strength steels commonly used in building structures in Korea. Steel is one of the main materials for building construction due to fast construction, light weight, and high seismic resistance. However, steel usually loses its strength and stiffness at elevated temperatures, especially over 600°C. But steel can regain some of its original mechanical properties after cooling down from the fire. Therefore, it is important to accurately evaluate the reliable performance of steel to reuse or repair the structures. For this reason, an experimental study was performed to examine the post-fire mechanical properties of steel plates SN400, SM520 and SM570 after cooling down from elevated temperatures up to 900°C. The post-fire stress-strain curves, elastic modulus, yield and ultimate strengths and residual factors were obtained and discussed.

Keywords: post-fire, mechanical properties, SN400, SM520, SM570, residual factors

1 INTRODUCTION

Steel has excellent mechanical properties at ambient temperature. However, like other materials, its strength and stiffness decrease at the elevated temperature. But steel can regain some of its original mechanical properties during the cooling phase and after cooling down from the fire. However, due to the fact that the residual forces and deformations will be developed during the cooling phase, it is important to accurately evaluate the reliable performance of steel structure after fire to determine reuse or repair the structure (Qiang et al. 2013).
Currently, there is no design standards contain information on the mechanical properties of steel after being exposed to fire. British Standard 5950 Part 8 (2003) Appendix B gives an advice about the reuse of structural steel after fire. According to this document, structural steel can be reused after fire if the distortions remain within the tolerances for straightness and shape. For mild steel S235 and S275, they can be assumed to be able to regain at least 90% of their mechanical properties. However, for S355, it can be assumed that at least 75% of the strength is regained after cooling from temperatures above 600°C. No assumption or suggestion is provided for more high-strength steels. Recently, Qiang et al. (2012) investigated the post-fire mechanical properties of steels of high-strength steels S460 and S690 using 5mm thickness of steel sheets and proposed predictive empirical equations for residual properties of them. Outinen and Makelainen (2004) conducted research on various structural steels at elevated temperatures and reported the post-fire mechanical properties of S355 steel using 3mm thickness of cold-formed steel taken from the corner part of square hollow section. Lee et al. (2012) conducted post-fire mechanical properties tests using 13mm thickness of steel plate obtained from web of A992 Gr. 50 WF section with different cooling method: (1) Cooling in blanket, (2) Cooling in air and (3) Cooling in water. However, post-fire mechanical properties on structural steel that is usually used for building structures are still limited and test results for high-strength steels are required.
This paper presents experimental studies on post-fire mechanical properties of commonly used mild to high-strength steels SN400 (KS D 3861; Nominal yield strength F_y = 235MPa), SM520 (KS D 3515; Nominal yield strength F_y = 355MPa) and SM570 (KS D 3515; Nominal yield strength F_y = 440MPa) after cooling down from elevated temperatures up to 900°C. In order to investigate the

post-fire mechanical properties of steel plates, tensile coupon tests were conducted and post-fire stress-strain curves, elastic modulus, yield and ultimate strengths and residual factors are presented.

2 TEST SPECIMEN AND PROGRAM

2.1 Test Material and Specimen

The most commonly used method to obtain the mechanical properties of steel is to conduct tensile coupon tests. Three different strength steel grades SN400, SM520 and SM570 were used to investigate post-fire mechanical properties of structural steels. The test specimens were machined from 12mm steel plate for SN400, and 60mm steel plates for SM520 and SM570 in the rolling direction. The major chemical composition and mechanical properties of the test specimens are presented in Table 1.

Table 1 Material properties of SN400, SM520 and SM570

Steel grades	Chemical composition (%)							Mechanical properties (MPa)		
	C	S_i	M_n	P	S	$C_{eq}^{1)}$	$P_{cm}^{2)}$	Yield strength (f_y)	Ultimate strength (f_u)	Yield ratio (f_y / f_u)
SN400	0.13	0.25	0.69	0.011	0.005	0.26	0.18	298	445	0.67
SM520	0.15	0.23	1.38	0.008	0.004	0.39	0.24	554	668	0.83
SM570	0.03	0.14	1.55	0.009	0.006	0.37	0.15	607	669	0.91

1) $C_{eq} = C + M_n/6 + S_i/24 + N_i/40 + C_r/5 + M_o/4 + V/14$

2) $P_{cm} = C + M_n/20 + S_i/30 + C_u/20 + N_i/60 + C_r/20 + M_o/15 + V/10 + 5B$

The shapes and dimensions of the specimens were prepared according to the International Standard ISO 6892-2. Each specimen had a circular section with the diameter of 6 mm and the gauge length of 30 mm. Test specimens for SM520 and SM570 were taken from the outside of plate thickness (= 60 mm). The details of the specimen are presented in Fig. 1.

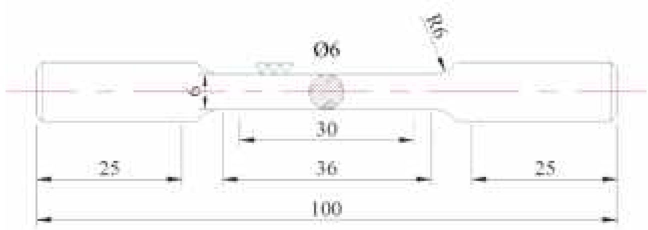


Fig. 1 Dimensions of tensile test specimen (unit: mm)

2.2 Test Program

To obtain post-fire stress-strain relationships of test specimens, the specimens were heated to a pre-selected temperature under the uniform heating rate of 10°C/min then maintain target temperature during 10 minutes for a stable temperature distribution, and then tensile tests were conducted after the specimens were cooled in air. In this study, the heated target temperatures were 100°C, 200°C, 300°C, 400°C, 500°C, 600°C, 700°C, 800°C, and 900°C.

The tensile tests were conducted using 100kN capacity of Instron universal testing machines (UTM). During the test, regardless of temperature, the strain rate of 0.015/min was applied up to the yield point. After yielding, the strain rate was increased to 0.12/min. Three specimens were tested at each target temperature and test specimen without heat treatment was also tested for comparison.

3 TEST RESULTS

3.1 Stress-Strain Curves and Failure Mode

The post-fire mechanical properties were investigated based on these stress-strain curves. The typical post-fire stress-strain curves of SN400, SM520 and SM570 after cooling down from various fire temperatures obtained from the test are presented in Fig. 2. As shown in Fig. 2, there is no difference in stress-strain curve up to exposed fire temperature of 700°C regardless of steel grades. However, differ from SN400, the residual strength of SM520 and SM570 steels were degraded from 800°C. In case of the fire exposed temperature of 900°C, elongation of SM520 and SM570 specimens were increased to 40% which is similar to that of SN400 steel. In addition, every specimen shows ductile failure mode with necking at the center of the specimens, no brittle failure is observed no matter how the fire exposed temperature is increased to 900°C. However, it needs to be noted that the specimens exposed fire temperatures above 700°C showed flaking at the surface of the specimen in the form of oxidization. The effect of heat caused visible damage to specimen’s surface after this temperature.

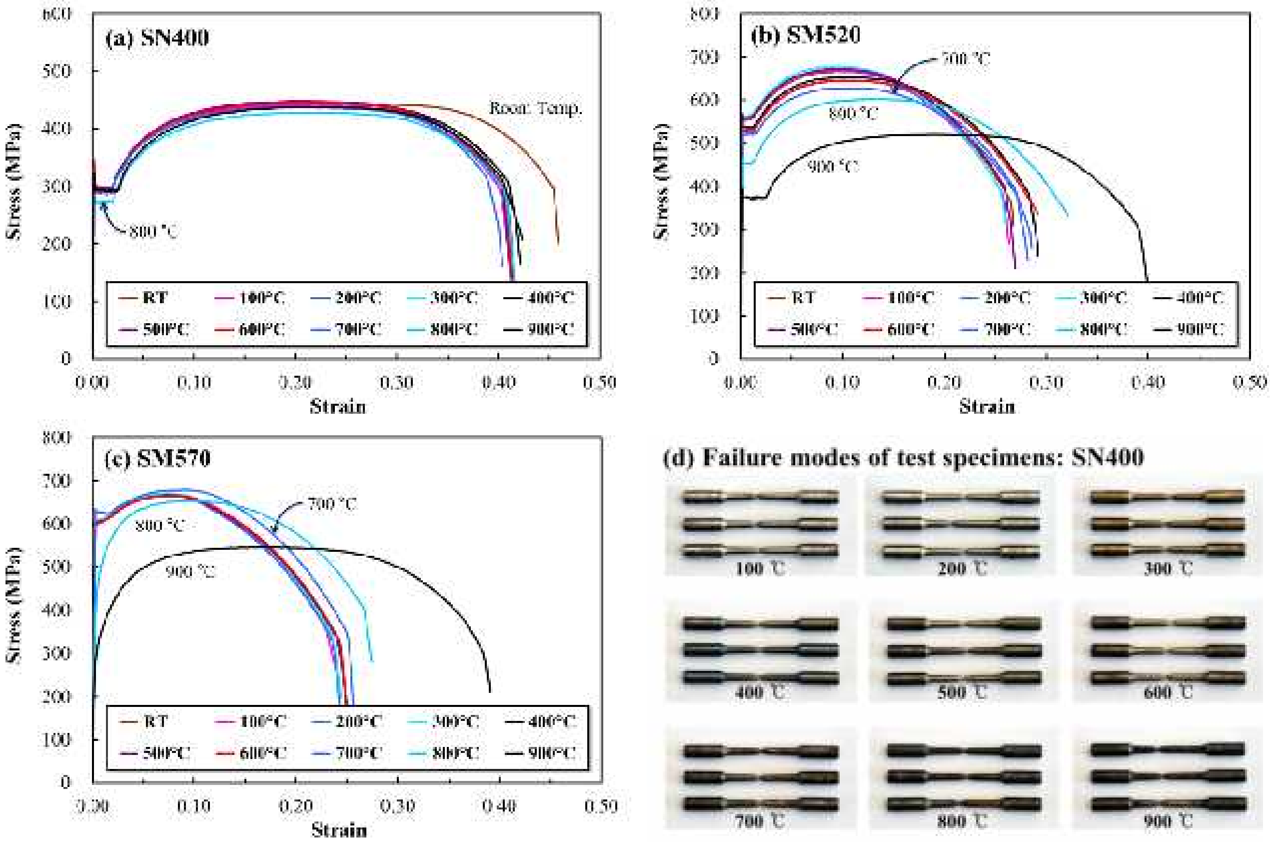


Fig. 2 Post-fire stress-strain curves after exposed to different temperatures

3.2 Elastic Modulus

Elastic modulus of the specimen was determined from stress-stress curve of steel after exposed to target temperature. The elastic modulus reduction factor for exposed fire temperatures was calculated as the ratio of the elastic modulus after being exposed to an elevated temperature to that of room temperature. Fig. 3 shows the elastic modulus reduction factors for SN400, SM520 and SM570. As shown in Fig. 3, for mild steel SN400 and SM520, the modulus of elasticity remained relatively unchanged and it was regained after exposed to fire. However, high-strength steel SM570 loses its elastic modulus after 700°C and it is steadily decreased by 15 – 25% as the exposed temperature increased to 900°C. The difference in residual elastic modulus between mild steel SN400 and SM520 and high-strength steel SM570 may result from different tempered conditions during manufacturing process.

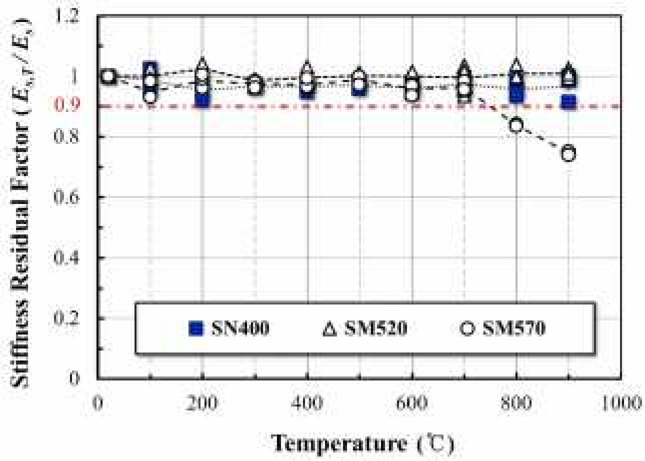
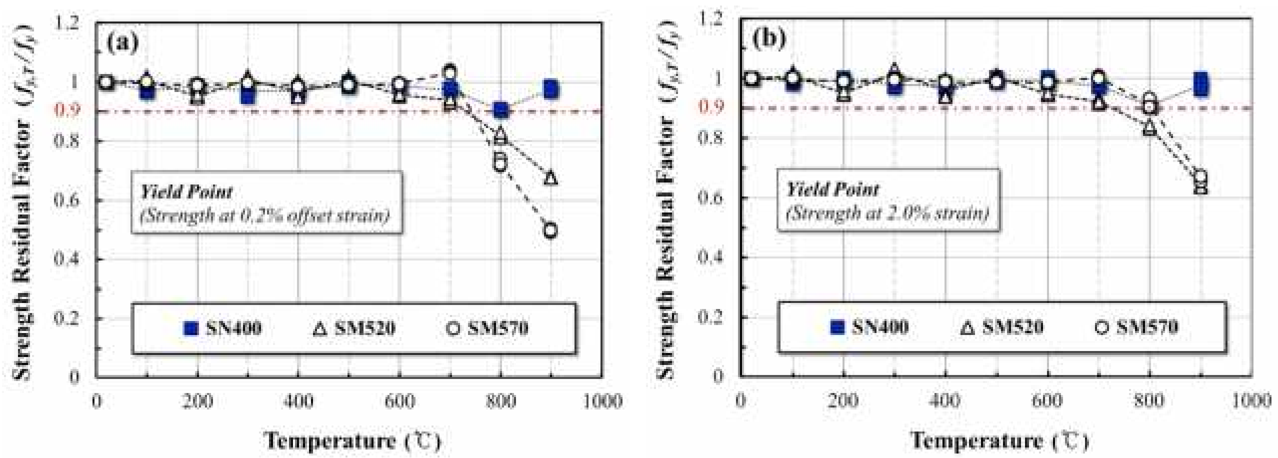


Fig. 3 Post-fire elastic modulus residual factors

3.3 Yield Strength

To obtain the yield strength of steel the 0.2% offset ($f_{0.2,T}$) method and 0.5% ($f_{0.5,T}$), 1.5% ($f_{1.5,T}$) and 2.0% ($f_{2.0,T}$) total strain levels are used. In the 0.2% offset method, the yield strength is determined from the intersection of the stress-strain curve and the proportional line offset by 0.2% strain level. The yield strengths at the strain level of 0.5%, 1.5%, and 2.0% are defined as those values corresponding to the intersection of stress-strain curve and the non-proportional vertical lines at given strain levels.

After exposed to various elevated temperatures, the post-fire residual yield strengths of SN400, SM520 and SM570 steels were obtained. Then yield strength residual factors after cooling down from elevated temperatures were calculated as the ratio of yield strength at elevated temperatures to that of no heat treated room temperature (see Fig. 4). As shown in Fig. 4, the post-fire yield strength of mild steel SN400 is almost not affected by the extent of fire exposed temperature and regains more than 90% of its original yield strength regardless of definition of yield strength. However, more high-strength steel SM520 and SM570 lose their yield strength when they are cooled down from elevated temperatures above 700°C. Due to the fact that the SM570 does now have yield plateau in stress-strain curve at high-temperature [see Fig. 2(c)], yield strength reduction factors of SM570 over 800°C are more rapidly decreased at the 0.2% offset method compared to that of SM520 as shown in Fig. 4(a). As a result, both SM520 and SM570 can regain their original yield strength if they are exposed to temperatures below 700°C. Also, it means that if the temperature of the steel members made of SM520 or SM570 are below 700°C and their distortions remain within the tolerances for straightness and shape, they are reusable after fire.



(a) 0.2% offset strain

(b) 2% strain

Fig. 4 Post-fire yield strength residual factors based on various strain method

Table 4. Post-fire yield strength (MPa) (Average values of 3 specimens)

Temp. (°C)	SN400				SM520				SM570			
	$f_{0.2,T}$	$f_{0.5,T}$	$f_{1.5,T}$	$f_{2.0,T}$	$f_{0.2,T}$	$f_{0.5,T}$	$f_{1.5,T}$	$f_{2.0,T}$	$f_{0.2,T}$	$f_{0.5,T}$	$f_{1.5,T}$	$f_{2.0,T}$
20	304	301	300	299	557	554	568	584	607	607	618	628
100	295	290	288	297	561	558	573	590	605	605	619	626
200	299	296	295	297	531	529	539	555	601	602	612	622
300	295	291	290	294	562	561	579	595	605	606	617	626
400	295	291	292	292	539	538	546	562	600	601	613	622
500	301	297	295	298	562	557	572	587	600	600	612	620
600	300	295	292	296	534	531	537	554	605	604	613	620
700	296	293	292	293	523	520	522	540	627	629	623	630
800	275	273	272	272	456	454	469	490	441	454	549	573
900	297	294	292	293	378	376	372	374	302	318	392	418

3.4 Ultimate Strength

The ultimate strength reduction factors were calculated based on the ratio of ultimate strength after being exposed to an elevated temperature ($f_{u,T}$) to that of no fire exposed room temperature (f_u). Fig. 5 present the residual ultimate strengths after exposed to elevated temperatures up to 900°C. The reduction factors in ultimate strength show a similar trend to those of yield strength. Thus, SN400 regain its original ultimate strength after exposed to fire temperature up to 900°C. However, both SM520 and SM570 lose their ultimate strength when they are cooled down from elevated temperatures above 800°C and those are become less than 90% at 900°C.

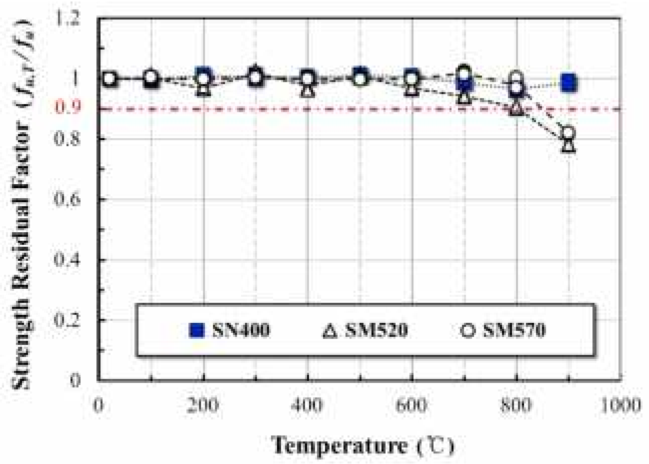


Fig. 5 Post-fire ultimate strength residual factors

4 CONCLUSIONS

An experimental study on the post-fire mechanical properties of commonly used structural steels SN400, SM520 and SM570 after cool down from elevated temperatures was presented in this paper. To obtain the post-fire mechanical properties, tension coupon tests were executed after cooling down form elevated temperatures from 100°C to 900°C. The elastic modulus, yield and ultimate strengths were determined from the based on stress-strain curves at each target temperature. The following remarks are made from the test results:

- Mild steel SN400 shows almost unchanged strength and stiffness after exposed to elevated temperatures except 800°C at which, however, the yield strength regained more than 90% of its original strength.

- High-strength steel SM520 and SM570 lose its original strength and stiffness when they are cooled down from elevated temperatures above 700°C. Thus, SM520 and SM570 can regain their original strength and stiffness if they are exposed to temperatures below 700°C.
- The steel grade and manufacturing process influenced on the yield strength and elastic modulus of steel after cooling down from the elevated temperatures.

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