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Hysteretic behaviour of high strength S690 steel materials under low cycle high strain tests

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ABSTRACT

This paper describes a detailed experimental investigation into structural behaviour of S690 steel materials under both monotonic and cyclic loading conditions. In addition to 6 monotonic tensile tests, which were conducted to establish basic mechanical properties, 36 cyclic tests were then carried out in order to examine hysteretic behaviour of the S690 steel materials under various target strains and loading frequencies. The experimental arrangements used for the monotonic and the cyclic tests are described, and a detailed account of the test results is provided. The monotonic tests showed that all the S690 steel specimens satisfied the ductility requirements stipulated in current European provisions which are typically based solely on monotonic behaviour. In the cyclic tests, most specimens were able to complete 20 cycles with target strain amplitudes of ± 2.5%, ± 5.0%, ± 7.5%, and ± 10.0%, under loading frequencies of 0.1, 0.5, 1.0 and 2.0 Hz. However, some specimens fractured at the 20th cycle when the target strains were ± 10.0% irrespective of the loading frequency. Additionally, significant strength enhancement due to strain hardening was observed and quantified in the cyclic tests, depending on the level of target strains. The results additionally illustrated the importance of using actual instantaneous cross-sectional diameters for evaluating true stresses in order to obtain actual representative hysteretic curves.

In general, the study highlights the importance of establishing seismic ductility requirements based on cyclic tests, particularly for high strength steel materials. It also provides a detailed assessment of the hysteretic characteristics, which can be directly employed to develop reliable constitutive models for high strength S690 steel materials under seismic loading conditions.

1. Introduction

Over the past twenty years, various grades of high strength steel materials, such as S690, S890, and S960, have been produced in many parts of the world, and they are highly attractive to structural engineers because of their high strength to weight ratios. These steel materials offer excellent mechanical properties, such as yield and tensile strengths as well as toughness, in comparison with normal strength steel materials. Wider adoption of high strength steel materials would lead to a significant reduction in sizes of structural members as well as self-weights of building structures, with improved constructability and leading to savings in overall construction time and costs.

According to modern structural design standards, such as EN 1993-1-1 [4], various ductility requirements for S235 to S460 steel materials, which are quantified according to mechanical properties derived primarily from monotonic tests, are stipulated as follows:

(i) tensile to yield strength ratio, $f_u/f_y \geqslant 1.10$, (1a)

(ii) strain at fracture, $\varepsilon_L \geqslant 15\%$, and (1b)

(iii) strain corresponding to tensile strength, $\varepsilon_u \geqslant 15 f_y/E_s$. (1c)

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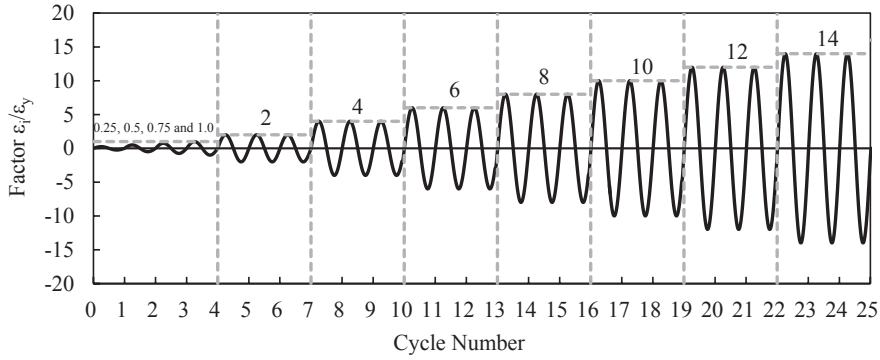
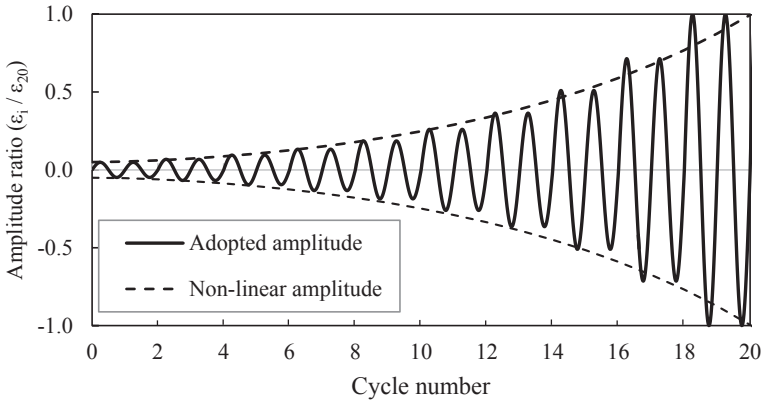
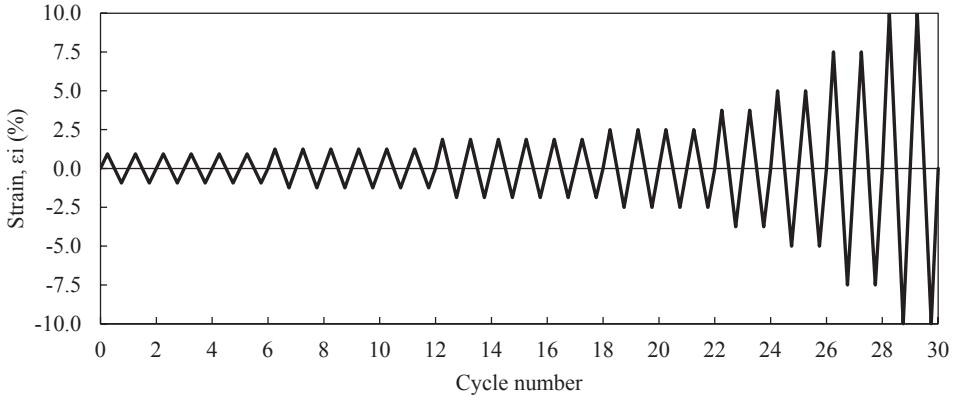


a) Loading protocol to ECCS



b) Loading protocol to FEMA-461



c) Loading protocol to AISC 341

Fig. 1. Comparison among three recommended loading protocols.

Table 1
Max % of chemical compositions.

Steel Grade		C	Si	Mn	P	S	N	B	Cr	Cu	Mo	Nb	Ni	Ti	V	Zr
S690	BS EN 10025-6	0.22	0.86	1.8	0.025	0.012	0.016	0.006	1.6	0.55	0.74	0.07	2.1	0.07	0.14	0.17
	Test	0.137	0.22	1.377	0.010	0.0012	0.004	–	0.33	0.485	0.24	0.026	0.037	0.012	–	–

For S690 steel materials, the minimum value of f_u/f_y is revised to 1.05 while the value of ε_L is re-defined to be $\geq$10% according to EN 1993-1-12 [5]. It should be noted however that typically no additional ductility requirements on steel materials are currently specifically stipulated for applications in seismic resistant structures.

As the structural behaviour of steel materials under cyclic loading differs from that under monotonic tests, it is important to establish ductility requirements based on cyclic tests on steel materials, especially for high strength steel materials, such as S690, to be qualified for use in seismic resistant structures.

In recent years, a number of studies reported cyclic tests on specifically designed coupons of various types of steel materials to examine their hysteretic characteristics under idealized pre-defined displacement histories. Such investigations (e.g. [9,10,24,18,22,6,29]) examined the hysteretic behaviour of structural steel materials using various testing methods reflecting different applications and