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Evaluation of High-Deformation Capability and High-Strength Steels as Reinforcement in Reinforced Concrete Members

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Abstract

In this study, use of a type of steel, which features high deformation capability and high yielding strength (≈540 MPa) as reinforcement in reinforced concrete members, is analyzed experimentally and analytically. The experimental portion of this study covers experiments with reinforced concrete members, which were tested under monotonic and reversed cyclic loads. These members were produced using two types of steel; one is the reinforcement steel which was used in the production of the members named “HSS”, with high strength and deformability capacity, and the other is BCIII steel, generally used in the construction industry of Turkey. Within reinforced concrete member experiments, full-scaled prefabricated columns and full-scaled reinforced concrete beams were tested. Damage distributions of the same loading pattern were made for comparison purposes. The aim of the experimental program was to especially analyze stiffness, ductility, and earthquake performance characteristics of the members. Analytical studies contain section analyses for reinforced concrete members with HSS and BCIII steel. These members include experimentally analyzed full-scaled, prefabricated columns. The experimental and analytical results showed that beams reinforced with “HSS” exhibited more strength and toughness, in comparison with the ones produced with BCIII. And reinforced concrete columns reinforced with “HSS” steel reached bigger moment and lateral load carrying capacities in comparison with the ones reinforced with BCIII. Singular reinforced concrete elements like beams reinforced with “HSS” were found to have more energy absorption capacity than the ones with BCIII.

Keywords: High Strength, High Deformation, Reinforcement Steel, Reinforced Concrete Members

Introduction

In the field of structural engineering, a lot of approaches and strengthening technologies in order to mitigate the effects of earthquakes on buildings have been developed over the years. One of the most important characteristics of a structure which is in earthquake regions is its ductility. A better ductile behavior can be achieved by constructing these structures with elements which have high energy absorption capacities during moderate and strong earthquakes. For reinforced concrete structures the deformation capability and strength of structural steel as reinforcement has an important contribution on the entire behavior of the reinforced concrete member**.** These circumstances pioneered the authorities to improve seismic standards. On these account seismic reinforcement steels are featuring in current seismic standards of many different countries like New Zealand, United States, England and various European countries.

The steel used in this paper 'HSS' can be classified as a seismic reinforcement steels. The following properties are defined for steel for being classified as seismic reinforcement.

- The ratio of its ultimate tensile strength (Rm) to yielding strength (Re) must be (Rm / Re) > 1.15 .
- Instead of ultimate elongation during rupture, the strain in the steel corresponding to the maximum stress in the bar, also defined as the uniform elongation (A_{gt}), must be taken into account.
- The strain in the steel corresponding to the maximum stress in the bar, also defined as the uniform elongation (A_{gt}) must be A_{gt}>6.

Influence of the seismic reinforcement steels to reinforced concrete structures has been studied by many different researchers. Sinha and Ferguson (1964) investigated the behavior of columns and beams reinforced with steels which have high yielding strength (690 MPa). They have reported that the toughness of the members reinforced with these steels is more than the ones reinforced with conventional steels. Allington and Bull (2002) presented the mechanical properties of seismic reinforcement steels which are featuring in New Zealand seismic standards. Bull and Allington (2002) reported that the change from Grade 430 reinforcement with a yielding strength of 430 MPA to Grade 500 (500 MPa) will have a number of implications in the behavior of concrete structures. Seliem (2007) investigated the use of high performance steels in reinforced concrete bridges. He reported that the use of high-strength reinforcement steels in reinforced concrete columns can increase the axial load carrying capacity of the column. Yotakhong (2003) investigated the behavior of beams experimentally. And he presented that beams reinforced with high-strength steels exhibited ductile flexural failure. Okada et. al (1984) studied the behavior of beams reinforced with steels which have yielding strength varying from 500-700 MPa experimentally. They found that the flexural rigidities after cracking and shear strengths of the reinforced concrete beams were found to decrease when the tensile steel ratio, for a given ultimate flexural strength, is lowered by use of high strength bars. Megget (2005) tested four external reinforced concrete beam-column sub assemblages reinforced with high strength steels under pseudo-seismic cyclic loading. He also compared the behavior of these members with the ones reinforced with normal strength steels. He concluded that the stiffness of the high-strength steel members were significantly less than same members reinforced with normal strength steels. Zhu and Lv (2011) investigated the application of high strength steel fiber reinforced concrete as a new type of structural material, and indicated it has unique advantages and wide application prospects. Ansely (2002), found that beams which are produced by high strength steels have higher toughness than the ones produced by normal strength steels. Another conclusion he obtained was the beams reinforced with ultra-high strength steels which have yielding strength of ~800 MPa have extremely higher maximum stiffness than the ones produced with normal strength steels. El Hacha and Rizkalla (2002) , concluded that the columns which are produced by normal strength steels have a failure mode result from the yielding of the reinforcement steel while the ones reinforced with high strength steels have a failure mode result from failure of the concrete.

This paper presents use of a type of steel, which features high deformation capability (A_{gt}=%8) and high yielding strength (≈540 MPa) as reinforcement in reinforced concrete members. The behavior of the reinforced concrete members are analyzed both experimentally and analytically. These members include full scaled prefabricated columns and full scaled beams. To compare the behavior of this steel, members reinforced with normal strength steels are also analyzed. The experimental and analytical results are presented by graphical representations with hysteretic and energy absorption curves. With these kinds of investigations ductility, rigidity and behavior of the reinforcement steels are compared.

Experimental Studies

Within the scope of experimental studies full scaled reinforced concrete columns and full scaled reinforced concrete beams are analyzed. Details of the dimensions and reinforcement of the columns are shown in Figure 1. The experimental setup and details of beams are given in Figure 2. Each of the beam and column experiments covers two specimens. Both of the columns and beams with identical cross-section were reinforced using HSS steel and conventional BCIII steel and tested to failure using the same loading configuration. The areas of the longitudinal and confinement steels were the same for both columns and beam pairs. The only difference was the type of reinforcement steel used in the specimens. Mechanical properties of these steels are presented in Table 1. The concrete used in the specimens has an average concrete compressive strength of 25 MPa.

Figure 1. *Dimensions of Column Specimen*

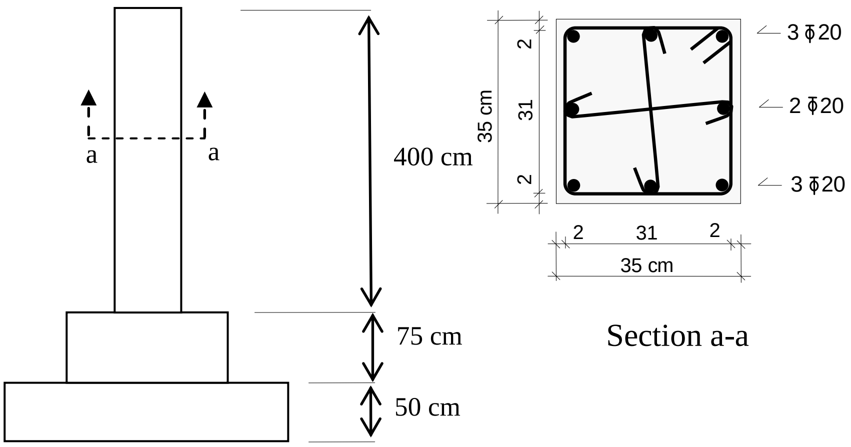


Figure 2. *Schematic Experimental Setup of Beams*

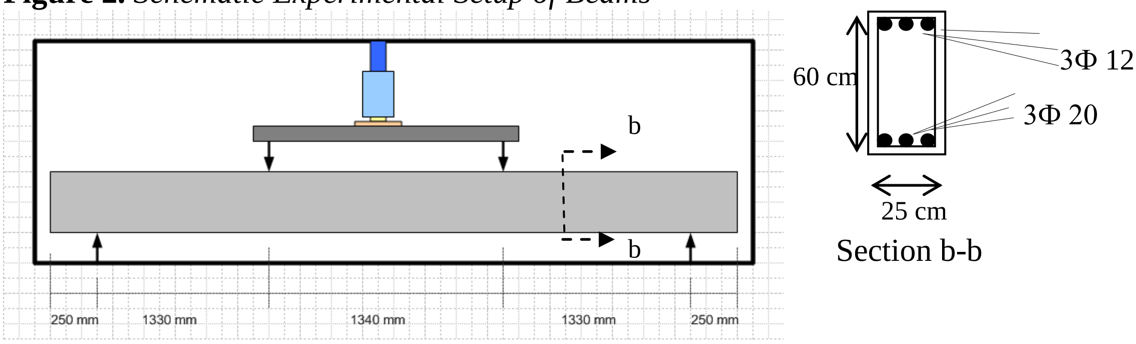


Table 1. *Mechanical Properties of HSS and BCIII Steel*

	Yielding Strength (MPa)	Tensile Strength (MPa)	A_{gt} (%)	R_e/R_m
HSS	500-650	600	8	>1.15-<1.35
BCIII	420	500	6	

For columns bending failure mode is descent. These induced increased usage of confinement steel during construction in possible plastic hinge locations. A diameter of 8 mm confinement steel was used with a spacing of 10 cm near column-foundation joint area, while spacing was 20 cm in the top region of the column.

Column Experiments

The columns are tested under reverse cyclic loading. An axial load of 280 kN is applied to both column specimens. This axial load corresponds to %10.5 of the total axial load carrying capacity of the column section, (N/N_g=%10.5) where N is the applied axial load during experiments and N_g is the axial load carrying capacity of the column. Same loading protocols were applied to the column pairs during experiments. The loading pattern is shown in Figure 3. As it can be indicated from Figure 3 the loading protocol was applied with an initial displacement of 1 mm and final displacement of 240 mm. Both cycles are implemented three times by pushing and pulling the top of the columns. Axial load is applied to the column with a hydraulic jack from the top. The schematic experimental setup and a scene from the experiments are given in Figure 4. Both strains of the reinforcements and displacement of the designated points of the column specimen are recorded during experiments. Strain-gages are used to measure the strains of reinforcement steel while transducers are used to measure the displacements of various points all over the columns.

Figure 3. *Loading Pattern of Column Experiments*

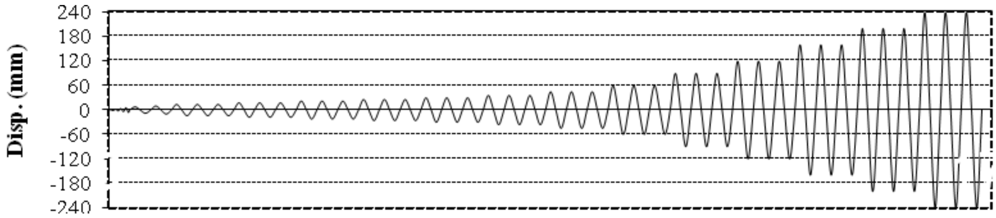
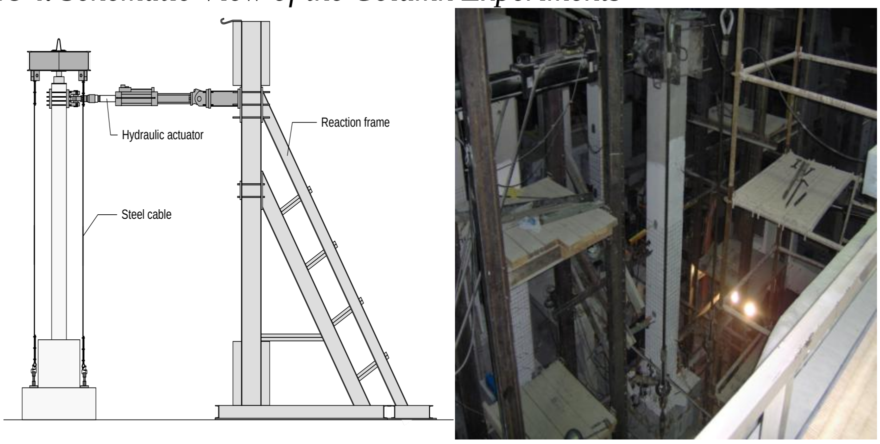


Figure 4. *Schematic View of the Column Experiments*



Columns are named according to their reinforcement. The one with normal strength BCIII steel named ‘PCN’ while the other with HSS steel named ‘PCS’. All the damages during the experiments are investigated by giving a break in each cycle and measuring them.

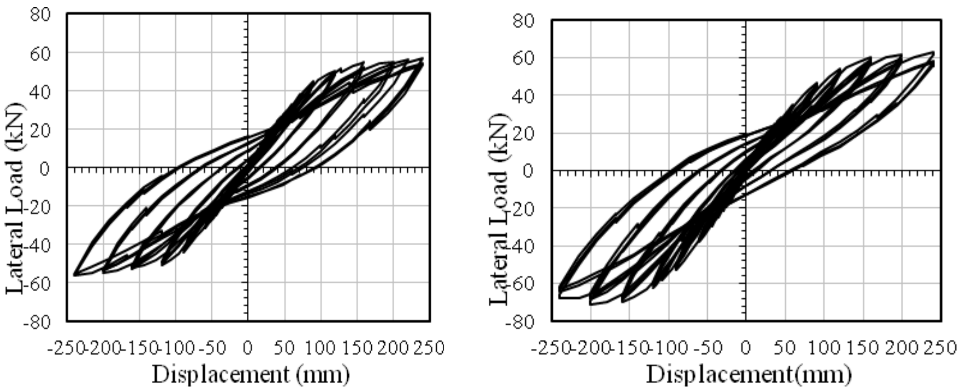
For PCN specimen first crack is observed in 6 mm cycle and the thickness is around 1 mm. And it is observed in same cycle for PCS with a thickness of smaller than 1 mm. First yielding of the reinforcement steel occurred in 18 mm cycle for PCN while it is in 45 mm cycle for PCS. Rupture in column base is observed in 90 mm cycle for PCN while it is observed in 105 mm in PCS. Collapse in compression zone of the column is observed in 220 mm cycle for both specimens. During the experiments rupture and buckling of the reinforcement steels are not observed.

There is a big difference in the yielding behavior of the reinforcement steels. HSS steel with high strength and high deformation capability exhibited this positive behavior in reinforced concrete column experiments.

Moreover the lateral load carrying capacities and displacement of top of the columns are measured during experiments. Hysteretic (load displacement) curves for two specimens are given in Figure 5. As it can be indicated from figure 5, PCS specimen has a bigger lateral load carrying capacity than PCN specimen. The load carrying capacity of PCS is %27 higher than PCN.

Figure 5. *Hysteretic Curves for Columns (a):PCN, (b):PCS*

(a) (b)



Beam Experiments

Simply supported beams are subjected to monotonic loading experimentally. The span of the beams is L=4m. One of the aims of the experiments is investigating the behavior in positive moment region. The design of the beams considered bending failure mode. Thus the design obtains the reinforcement steel to achieve maximum performance. Moreover to avoid shear failure necessary precautions are taken during experiments.

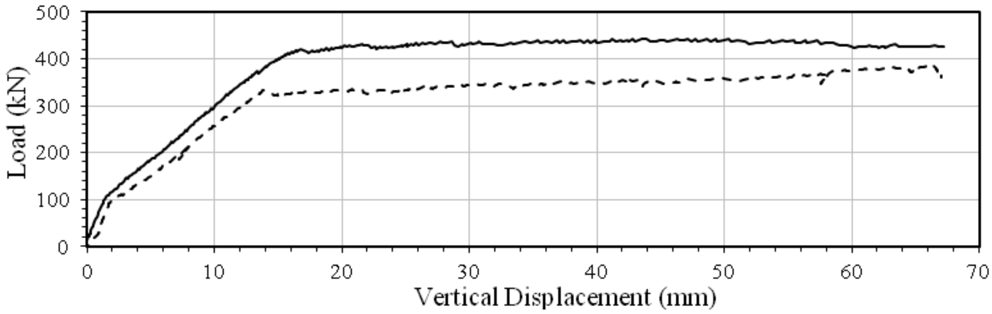
The beams are named according to their reinforcement. The one with normal strength BCIII steel named ‘BN’ while the other with HSS steel named ‘BS’. As presented in Figure 2 the experiment is designed like four point bending beam test. Forces are applied from the top of the beam with a distance of 1/3 L. There are two identical single loads applied to the beam. In the experimental setup single loads are exerted to the beam specimens as reactions of the rigid beam (see Figure 2). Deflections and rotations of the beam are measured by linear variable differential transformers LVDT and strain gages are used to measure the strains of reinforcement steels. Experimental setup, rigid loading beam and measurement system of beam experiments are given in Figure 6.

Figure 6. *Experimental setup of BN and BS specimens*

Only vertical load is applied to the beams during experiments. The beams are loaded until collapse. Damages of the beams are examined during experiments by measuring the cracks and their thickness. For both BS and BN beams vertical cracks are observed in the constant bending moment zone while diagonal cracks are observed in the zones near supports.

Load displacement curves are given in Figure 7 in a comparative way for BS and BN. The maximum vertical displacement of BS is %27 higher than BN. As it can be indicated from Figure 2, BS achieved bigger displacements and loads than BN. BS beam which is produced by HSS steel showed ductile behavior by keeping the maximum load carrying capacity while approaching collapse although the BN beam showed strain hardening behavior after a short yielding region.

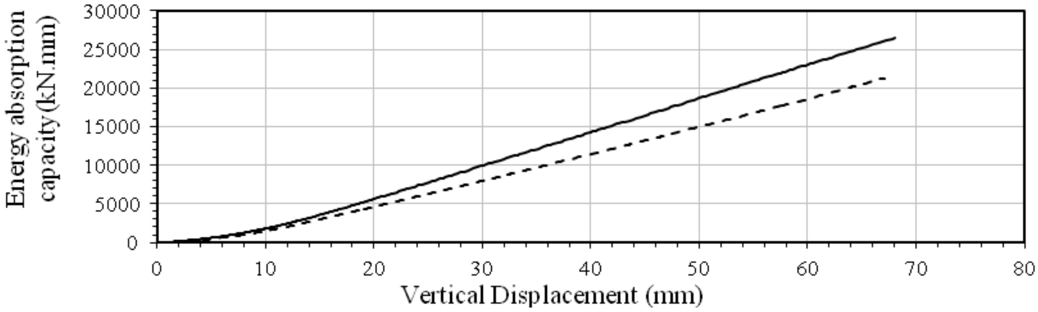
Figure 7. *Load displacement curves for BN and BS specimens (BN: dashed line, BS:solid line)*



The yielding of reinforcement steel in both BN and BS occurred in 20 mm displacement of the beams. Although the yielding occurred in same displacement level for both specimens, load carrying capacity of BS is %28 higher than BN during the yielding level of reinforcement steel.

Moreover energy absorption behavior of the beams is investigated and comparative energy curves for the beams are given in Figure 8. As it is presented in Figure 8 BS achieved better energy absorption performance than BN. Maximum energy absorption capacity of BS is % 22 higher than BN.

Figure 8. *Energy absorption curves for BN and BS specimens (BN: dashed line, BS:solid line)*



Analytical Studies

In this section the behavior of the full scaled columns which are tested experimentally is investigated analytically. Pushover analysis are performed with a software named COLA (Reinforced Concrete Column Analysis), Yalcin and Saatcioglu (2000).

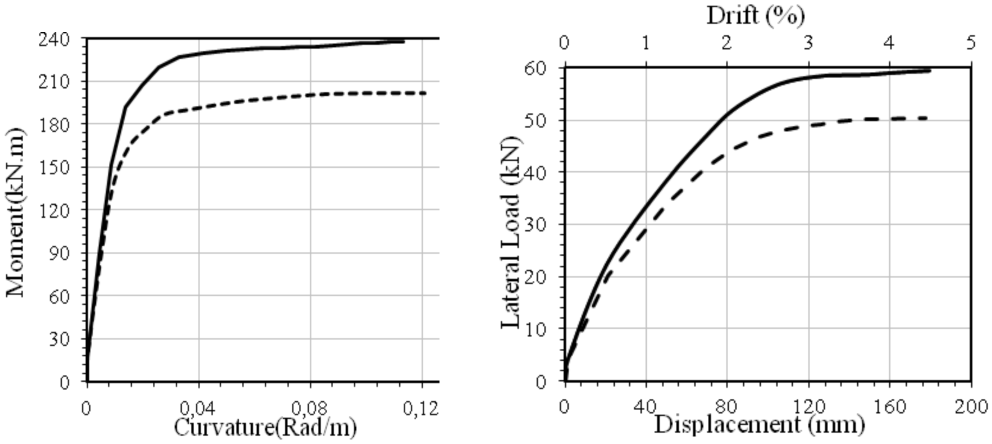
The analytical studies of the columns consider the effect on confinement of concrete, strain hardening behavior of steel, buckling of reinforcement steel and
P-delta effect. Columns are assumed as attached to a rigid foundation in analytical calculations. Mechanical properties of the reinforcement steel HSS, BCIII and concrete which are used in the experiments are defined to the software. For HSS steel the material model is obtained by considering steel pullout tests of this material. For BCIII steel common material model of the steel is defined to the software. The material model used for concrete is Hognestad concrete model with an average concrete compressive strength of 25 MPa.

As well as the experimental column analysis , analytical studies cover two columns, one of which reinforced with HSS steel and named 'CS' while the other with BCIII steel named 'CN'. The dimensions, section properties and reinforcement ratios of the columns are identical with the ones which were tested experimentally (see figure 2). In addition axial load of 280 kN is applied to both column specimens as experiments.

Moment curvature, load displacement and energy absorption behavior of these columns are investigated analytically. The results are given in a comparative way for CS and CN in Figure 9. Drift ratios are also included in the load displacement curve. It can be indicated from figure 9 that CS column reinforced with HSS steel reached bigger moment and load carrying capacities than CN column reinforced with normal strength steel. Maximum moment capacity of CS is %18 higher than CN column while load carrying capacity of CS is %19 higher than CN.

Figure 9. *(a):Moment curvature (b):Load-displacement-drift relationships for columns (CN: dashed line, CS:solid line)*

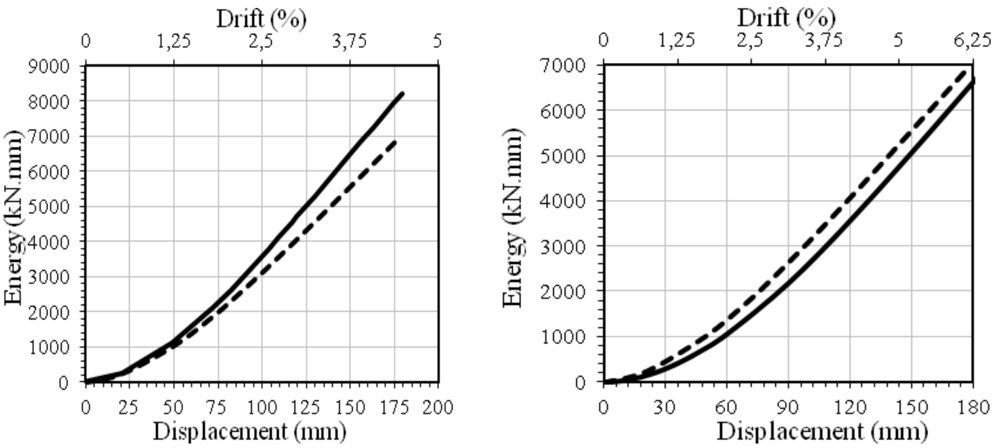
(a) (b)



In addition energy absorption behavior which can give an idea about the ductility of the columns is presented in Figure 10-(a) for both columns. As shown in Figure 10 (a) CS column absorbed bigger amount of energies than CN column for all drift ratios. Maximum energy absorption capacity of CS column is %18 higher than CN column. Figure 10-(b) represents the comparison of the energy behavior of experimentally tested PCN and analytically investigated CN columns. As it is presented in Figure 10-(b) there is a good match between experimentally tested and analytically calculated energy behavior of the columns.

Figure 10. (a*):Energy absorption relationships for columns (CN: dashed line, CS: solid line) (b):Comparison of experimental and analytical results (experimental: solid line, analytical: dashed line)*

(a) (b)



Conclusions

This research addresses the effectiveness of high strength steels as reinforcement in reinforced concrete members. Experimental results illustrate that beams reinforced with high strength steel have higher energy absorption and stiffness capacity than the ones with normal strength steels. High elongation capability and high strength HSS steel which showed better behavior in steel pull-out tests exhibits similar behavior in reinforced concrete member tests. The high deformation capability of HSS steel is also observed in the reinforced concrete member experiments. The initial yielding of the high deformation capability and high strength steel occurred in a higher displacement level (2.5 times higher) than the normal strength steel in column experiments. Moreover it has been both experimentally and analytically shown that columns reinforced with high deformability and high strength steel has higher energy absorption and stiffness capacity than the ones with normal strength steel. Thus their ductility is found to be higher than the ones reinforced with normal strength steel. Further study can be experimental analysis of low-story frame structures reinforced with high strength and normal strength steels and illustrating the effectiveness of the use of this type of reinforcements in structures experimentally.

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