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Performance based seismic analysis of stainless steel reinforced concrete bridge pier using damping ductility relationship

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ABSTRACT: Stainless steel is gaining popularity as structural member due to its corrosion resistance, improved performance against fire and resilient behavior. Performance based seismic design (PBSD) method is a viable alternative of current forced based design approach more particularly for the structures subjected to seismic loading. The equivalent viscous damping plays an important role in determining the performance of the structural components in PBSD method to observe the damping-ductility relationship for stainless steel (SS) reinforced bridge pier. This paper aims to investigate the ductile performance of SS reinforced bridge pier due to its hysteretic damping behavior using direct displacement based design method. Upon completing experimental investigation for tensile properties of the SS rebar's, nonlinear time history analysis is performed for ten different earthquake records to observe and compare the hysteretic behavior of SS reinforced bridge pier with that modeled for conventional carbon steel reinforced bridge pier. The performance of the proposed SS reinforced bridge pier is also compared for maximum lateral displacement resulting from different time histories.

1 INTRODUCTION

In last few years seismic hazard has become a big concern for civil engineers. Due to potential earthquake disasters, damages occur in structures which lead to fatalities and injured people. So the concepts of performance based seismic design (PBSD) of structures become a matter of consideration in designing structures instead of traditional forced based design system. Different research has been done on feasibility of performance based design in cantilever reinforced bridge. Kowalsky et al. (1995) presented the procedure for direct displacement based design (DDBD) of RC bridge column in seismic regions. Alam et al.(2016) investigated the application of shape memory alloy (SMA) in bridge pier by developing performance based damage states in PBSD method. Priestley et al (2007) developed DDBD system where a single degree of freedom system is subjected to a target displacement under specified seismic intensity and structure is designed to achieve a specified performance limit state defined by strain. In case of force-based seismic design a structure is characterizes by pre-yield, elastic damping and initial stiffness but in DDBD the structure is characterizes by secant stiffness at maximum displacement and represents the equivalent viscous damping (EVD) property which is combination of both elastic damping and hysteretic energy dissipation during inelastic state. Equivalent viscous damping represents the energy dissipation capacity of structure by suppressing the structural response under seismic excitation.

Stainless steel is expected to show different hysteretic behavior than conventional steel used as reinforcement in structures. Many studies has been done on the applicability of stainless steel in seismic design due to the higher value of ductility it shows over mild steel. Stainless steel contains more than 10.5% chromium and less than 1.5% carbon which make this alloy corrosion resistance. Among different grades austenitic steel is used for 70% of global production as it contains 8-13% nickel which makes this more ductile (Gardner, 2005). In seismic regions, using stainless steel is favorable because it combines higher strength and elongation with light weight compare to the carbon steel. A typical comparison between carbon steel and stainless steel is presented in Figure1. However, local industries of Bangladesh manufacture stainless steel whose grade is quite different than other neighbor countries. The chemical composition of the SS rebar is presented on Table 1. The chemical of the stainless steel reflects that such properties and proportions of ingredients lies in 200 series SS (grade 201). In order to investigate the mechanical properties of this local stainless steel rebar's, tensile strength tests are conducted for few samples using universal testing machine as shown in Figure 2. Based on the tensile strength test data, the mechanical properties of SS rebar is presented in Figure3. The experimental results shows that the yield strength at 0.2% strength is 517 MPa with an ultimate strength of 717 MPa whereas the strain at ultimate strength of the SS rebars (18%) is higher than that of the carbon steel. This data has been further used in the numerical analysis of the bridge pier conducted in this study.

Table 1. Composition of the local stainless steel.

Name of the Alloy	Percentage (Weight)
Carbon (C)	0.075
Silicon (Si)	0.292
Manganese (Mn)	10.22
Phosphorus (P)	0.026
Sulfur (S)	0.002
Nickel (Ni)	1.13
Chromium (Cr)	13.8
Copper (Cu)	0.820
Iron (Fe)	Balance

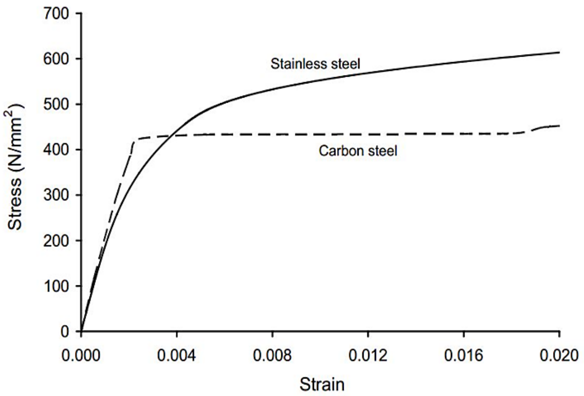

Figure 1. Typical mechanical properties of carbon steel and stainless steel.

Figure 2. Test Set ups and failure modes of the samples.

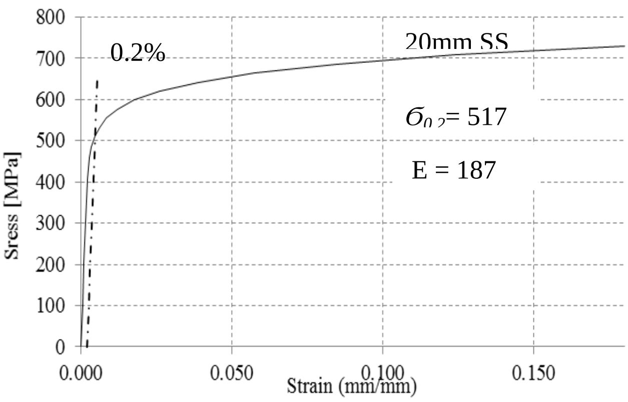

Figure 3. Mechanical properties of stainless steel grade 201.

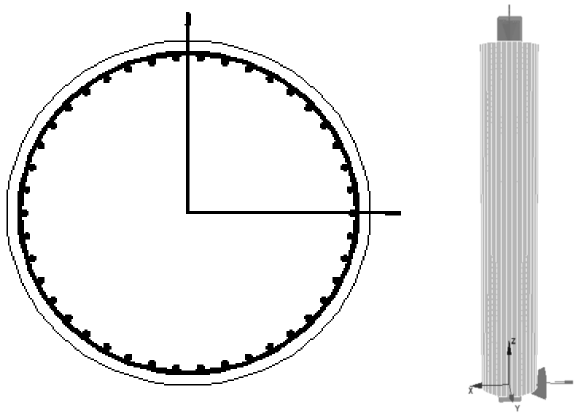

Figure 4. Cross section and elevation of SS reinforced concrete bridge pier.

The tensile strength of this material increases in cyclic loading rather than monotonic loading. For PBSD determining damping-ductility relationship and equivalent viscous damping is an important step. Priestly et al. (2007) and Dwairi et al. (2007) proposed equation (1) and (2) for determining equivalent hysteresis of steel member.

Priestley Equation: $\xi_{eq} = 0.05 + 0.577\left(\frac{\mu-1}{\mu\pi}\right)$ (1)

Dwairi Equation: $\xi_{eq} = 5 + 85\left(\frac{\mu-1}{\mu\pi}\right)$ (2)

In this paper Priestley equation is used to determine EVD reinforced bridge (SS-RC) pier which established the damping-ductility relationship for SS-RC bridge pier.

2 GEOMETRY OF BRIDGE PIER

The studied bridge pier was designed considering a constant diameter of 1.6 m and the column was reinforced with 42 longitudinal stainless steel bar of 28 mm diameter and 16 mm diameter stainless steel bars were used at 50 mm pitch. Aspect ratio 5 was selected which lead the height of the pier to be 8 m. The other properties used in this study such as elastic modulus, yield stress and strain are given in Table.

Table 2. Material properties.

Material	Property	Values
Concrete	Compressive Strength (MPa)	28
	Elastic Modulus (GPa)	24.8
	Tensile Strength (MPa)	2.2
	Strain	0.002
	Elastic Modulus (GPa)	187
Stainless Steel	Yeild Stress (MPa)	517
	Ultimate Stress (MPa)	728
	Ultimate Strain	0.18
Carbon Steel	Elastic Modulus (GPa)	207
	Yeild Stress (MPa)	550
	Ultimate Stress (MPa)	621

3 FINITE ELEMENT MODELING

The SS reinforced bridge pier was modeled in finite element software SeismoStruct 2020 where. Nonlinear time history analysis has been conducted to establish the damping ductility relationship of bridge pier. This software is capable of predicting large displacement under both static and dynamic load conidering both geometric nonlinearities and material inelasticities. The Menegotto-Pinto steel model with Monti-Nuti (1992) post elastic buckling was used for stainless steel reinforcement. The Menegotto-Pinto (1973) model was used for convetional steel reinforcement for modeling a mild steel reinforced bridge pier.For confined and unconfined concrete, the Mander et al. (1988) concrete model was used.

From the above consideration a bridge pier was reinforced with conventional steel reinforcement and other one was modeled with ductile stainless steel.

4 METHODOLOGY

Dwairi et al. 2007 and Priestley 2005 propsed different methodologies for establishing damping –ductility relationship of different structures. In this study Priestly equation is used for determining equivalent viscous damping and ductility relation. In oder to determine EVD for SS-RC bridge pier nonlinear time history analysis were carried out against ten different earthquake considering cantilever bridge pier. The procedure adopted are given below:

- At first initial column parameters were choosen. Height of column L= 8 m , Lumped mass M=1000 tonne. The other material properties are given in Table 1.
- A suitable ground motion was selected to cover a wide range of magnitude to determine the structural response.
- The target spectra was matched with different seimic ground motions.
- Nonlinear analytical model of bridge pier was developed and NLTHA was conducted for ten different earthquakes to determine hysteretic force-deformation relationship.
- Maximum displacement (Δ_u) and yeild displacement (Δ_y)were identified and after that ductility ($\mu=\Delta_u/\Delta_y$) was calculated.

– From Priestley EVD equation damping is calculated and from damping T_{eff} was determined. K_{eff} was determined from T_{eff} and mass equation.

5 DISPLACEMENT-BASED DESIGN PROCEDURE OF SS-RC BRIDGE PIER

A target spectra for suitable seismic zone was selected first according to Eurocode-8 which corresponds to 2% probability of exceedance in 50 years with a return period of 2500 years. It considers that the structure should not collapse but repairing is not possible economically.The selected different earthquakes acceleration was matched with the design spectra. The selected ground motions were also scaled to match with the displacement response spectra. The properties of ground motion that has been used in this study is presented on Table 3.

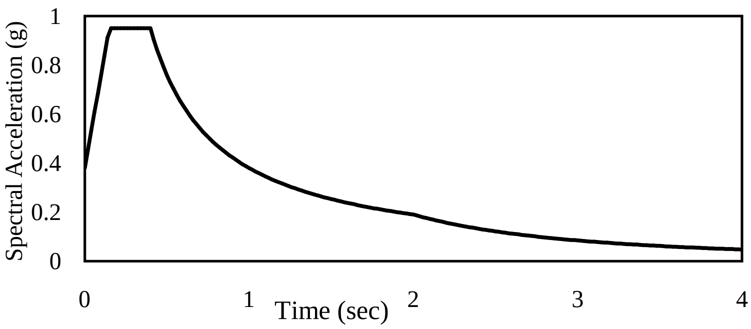

Figure 5. Design acceleration response spectrum.

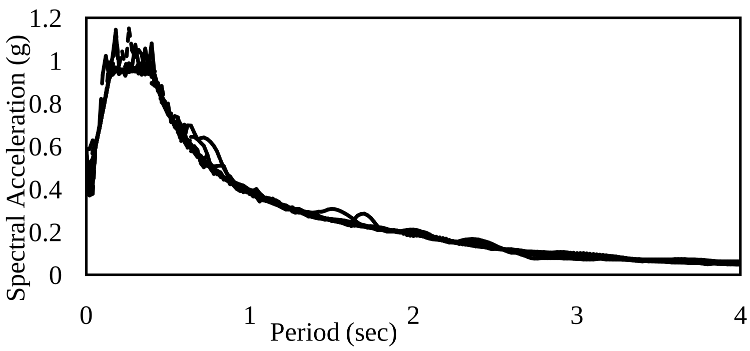

Figure 6. Matched accelerograms.

Table 3. Earthquake ground motions (Source: PEER ground motion database).

Number	Earthquake	Magnitude(M_W)	Date
1	Chi-Chi	7.7	09/21/1999
2	Imperial_Valley	6.8	10/15/1979
3	Kobe	6.9	01/16/1995
4	Loma Prieta	7.1	10/17/1989
5	Northridge	6.8	01/17/1994
6	Kocaeli	7.8	08/17/1999
7	Landers	7.5	06/28/1992
8	Trinidad	5.2	01/01/1996
9	Friuli	6.5	05/06/1976
10	Hollister	7.1	10/17/1989

The maximum drift was taken 4% for the designed damage level. Maximum displacement $\Delta_m = 0.04*8 = 0.32$ m. Initial column height was selected to be 8 m. The yeild drift was selected 1.5%. The yeild displacement $\Delta_y = 0.015*8 = 0.12$ m. so ductility demand, $\mu = \Delta_m / \Delta_y = 0.32/0.12 = 2.67$. From damping ductility equation proposed by Priestley for Ramberg-osgood hysteresis model of stainless steel the EVD was calculated.

$$\xi_{eq} = 0.05 + 0.577 \left(\frac{\mu - 1}{\mu\pi}\right) = 16.5\%$$

The spectral reduction factor (R_ξ) was found from the equation proposed by Priestley

$$R_\xi = \left(\frac{0.1}{0.05+\xi}\right)^{0.5} = \left(\frac{0.1}{0.05+0.165}\right)^{0.5} = 0.68$$

The displacement spectrum corresponding to 16.5% damping is obtained by using the reduction factor 0.68. Fig-4 shows the 5% damped and reduced damped displacement spectrum. From the reduced displacement spectrum and maximum displacement $\Delta_{m,}$ the effective time period T_{eff} was obtained as 3.40 sec. On the basis of effective time period the effective stiffness was calculated.

$$K_{eff} = \frac{4\pi^2\ M}{T_{eff}^2} = \frac{4\pi^2 \times 1000000}{3.4^2} = 3.42\ \text{MN/m}$$

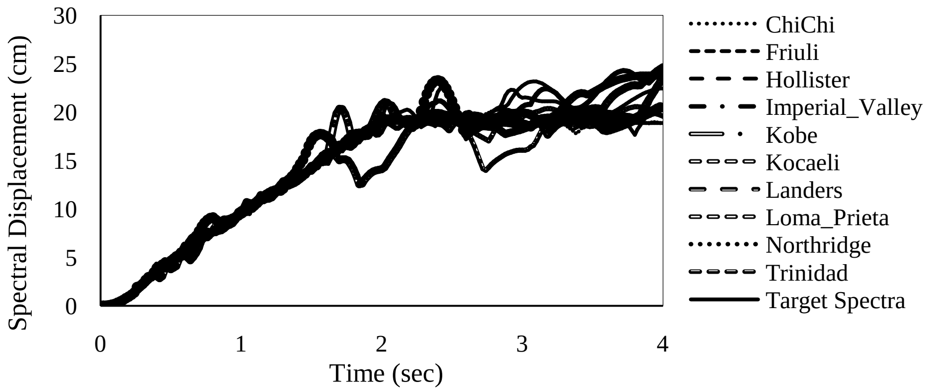

Figure 7. Displacement spectra of ten earthquake records matched with target response spectrum.

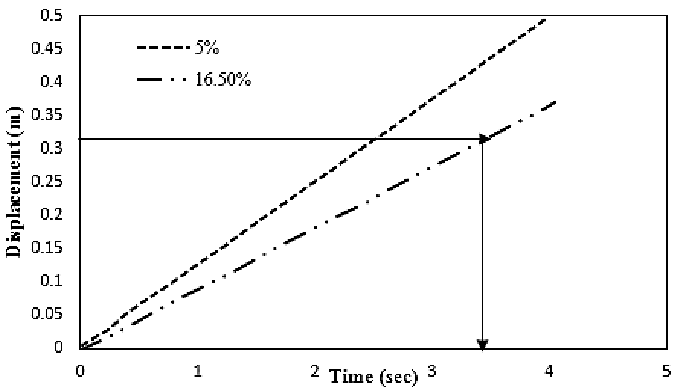

Figure 8. Time period determined from reduced displacement spectrum.

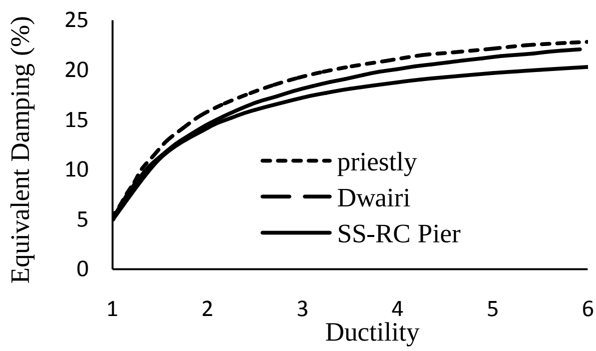

Figure 9. Comparison of damping-ductility curve.

The damping ductility relationship was developed by calculating EVD for each earthquake accelerograms with respect to ductility. The equivalent damping is the combination of elastic damping $\xi_0$which is normally taken as 5% and hysteretic damping ξ_{hyst} which largely depends on the energy dissipiation capacity of the structure. For SS-RC bridge pier Priestley EVD equation was used to observe the π-ξ relationship. The coefficient of determination R^2value was found more than 96% for this expression. From figure 5 it is also observed that the obtained equivalent viscous damping and ductility curve for SS-RC bridge pier is showing good accordance with both the proposed curve by Priestely et al. (2007) and Dwairi et al. (2007).

6 PERFORMANCE EVALUATION OF MS-RC AND SS-RC BRIDGE PIER

Appropiate eqivalent viscous damping is a function of total energy absorbed by the hysteresis of the structure during seismic excitation and here it is very imperative to investigate the histeritic behabior or bridge pier against seismic event. Time history analysis was conducted for both MS-RC and SS-RC bridge pier against ten seismic ground motions. Figure 10 shows the hysteritic behavior of SS-RC bridge pier and MS-RC bridge pier to compare their performance. It is observed from the analysis that SS-RC bridge pier shows more ductile behavior because of its higher capability to absorb more energy and hence resulting in a fatter hysteresis loop compare to that of MS-RC bridge pier. The hysteretic behavior of SS reinforce pier shows that the maximum base shear is found to be 1046 kN which is nearly 10% less than that of MS-RC pier. This pheonamenon ultimately shows the higher ductility of SS reinforced bridge piers. On the other hand, maximum dispacement of the SS-RC bridge pier is 40mm where as the maximum deflection of MS-RC brdge pier is 56mm to take the same magnitude of seismic demand. Therefore, the performance of the SS-RC bridge pier is significantly improved in term of energy absorption (i.e. ductility) and servicebility compare to the conventional MS-RC bridge pier.

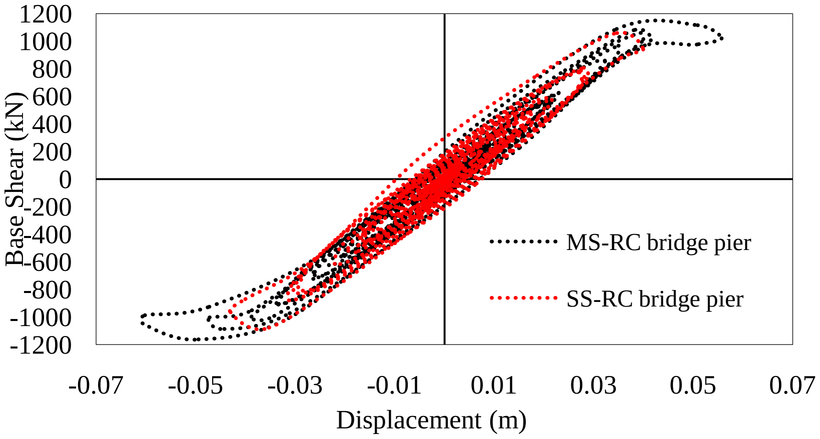

Figure 10. Hysteretic behavior of SS-RC bridge pier and MS RC bridge pier.

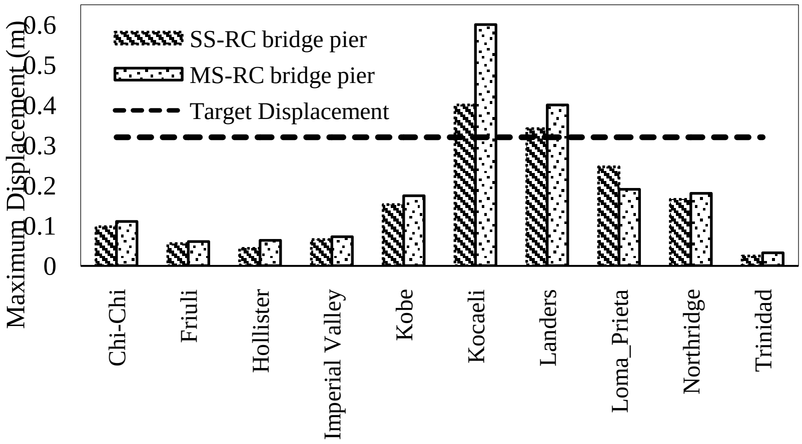

Figure 11. Maximum structural displacement for SS RC bridge pier compared with MS-RC bridge pier.

Maximum lateral displacement of both SS-RC and MS-RC bridge pier for ten different ground motions is presented on Fig-11. It is evident from the figure that SS-RC pier sustained mximum displacement from analysis among ten earthquakes. Only two out ten cases, maximum displacement exceeds the displacement margin and remaining eigth cases are within the design target displacement. The figure also shows that displacement of MS-RC bridge pier is higher than that for SS-RC bridge pier for all the time histories except Loma_prieta. In case of MS-RC bridge pier, two earthquake shows much higher displacement than the target displacement whereas SS-RC bridge pier lies close to the margin. This evidence proofs that in many cases of real life bridge design, SS-RC bridge pier may meet code requirement in terms of strength, lteral drift and serviceability where MS-RC bridge piers fail to do so. Therfore, SS-RC bridge piers shows improved performance expectations at different earthquake time histories.

7 CONCLUSIONS

In this study, locally manufactured stainless steel rebars are tested to obtain the mechanical properties. Chemical composition and mechanical properties suggest that the local stainless steel properties lie close to the grade 201 (i.e. 200 series). The test results are used to investigate a real life bridge pier using damping ductility relationship in light of performance based seismic analysis. The damping-ductility relationship curve obtained for SS-RC bridge pier showed good accordance with the proposed ramberg-osgood hysteretic model proposed by Priestley (2007). In this study, the coefficient of determination R^2 value for the damping ductility relationship was found more than 96%.

It is observed from the analysis that SS-RC bridge pier shows higher ductility by disssipiating more energy and forming a fatter hysteresis loop compare to that of MS-RC bridge pier. It is obseved from the hysteretic behavior of SS reinforced pier that the maximum base shear is 1046 kN which is nearly 10% smaller than that for MS-RC pier. Maximum dispacement of the SS-RC bridge pier is nearly 27% less than that for the MS-RC bridge pier considering the same magnitude of seismic demand.

In another observation from the ten different time history analysis is that SS-RC bridge pier exceeds the displacement mrgin only in two cases and remaining within the design target displacement in all other eigth cases. The figure also shows that displacement of MS-RC bridge pier is higher than that for SS-RC bridge pier for all the time histories. This evidence proofs that in many cases, SS-RC bridge pier will meet code requirement in terms of strength and serviceability where MS-RC bridge pier fails to do so. Therefore, the performance of the SS-RC bridge pier is way improved in terms of ductility and servicebility compare to the conventional MS-RC bridge pier at different earthquake time histories.

Stainless steel is useful and popular for structural design for its corrosion resistance property. So applying it in bridge pier can help reducing the long term maintenance cost and also its post-yield buckling characteristics reduces the structural damage probability under strong earthquake ground motions. Moreover, its energy dissipation capacity is larger than the conventional steel which makes it more structure resilient material.

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