Seismic Evaluation of Stainless Steel-Reinforced Concrete Bridge Pier Using Performance-Based Damage States

K. A. Farzana and K. S. Ahmed

1 Introduction

Bridges are an important means of transportation system everywhere in the world. For the sustainability of bridges in an earthquake event, collapse or damage assessments are essential criteria to consider in the structural assessment. So in recent years, increased interest has been grown among researchers to define performance objectives for structures. In performance-based design procedure, a structure is designed to attain specific performance levels under seismic excitation and an annual probability of exceedance of each level [1]. The post-earthquake functionality of bridge is predicted by limiting its damage and reducing residual deformation in PBD approach [1]. The structure is designed to behave more ductile by dissipating energy during seismic excitation and thus minimizing the repairing as well as maintenance cost substantially. Previously, performance-based seismic assessment of reinforced concrete bridge was conducted depending on the level of importance of bridge, and also the repairing techniques were mentioned for different performance levels [2–5]. An experimental program on a 1/3 scale bridge pier was conducted at BUET-JIDPUS laboratory, Dhaka under cyclic loading [6]. The damage of bridges causes economic and life loss during the earthquake. Therefore, the main focus of this research is to limit the damage of bridge to full operational level after a certain seismic excitation. The collapse vulnerability of the steel fiber-reinforced bridge pier was assessed previously by [7].

In order to enhance the resilience of structures against earthquake, the huge number of research work has been carried out using passive control such as isolators

K. A. Farzana (✉) · K. S. Ahmed
Department of Civil Engineering, Military Institute of Science and Technology, Dhaka, Bangladesh
e-mail: afia@ce.mist.ac.bd

K. S. Ahmed
e-mail: drksa@ce.mist.ac.bd

S. Arthur et al. (eds.), *Advances in Civil Engineering*, Lecture Notes in Civil Engineering 184, https://doi.org/10.1007/978-981-16-5547-0_15

or dampers [8–10]. For existing structure, seismic performance of structural column can be improved by concrete jacketing [11]. The stainless steel shows high ductility and corrosion resistivity than conventional carbon steel. It is known from the literature that stainless steel shows higher yield point, ultimate strength and higher strain hardening property than carbon steel [12, 13]. Under same seismic excitation, stainless steel-reinforced column shows less severe damage than reinforced with carbon steel by dissipating more energy due to its hysteretic behavior [14]. Stainless steel and carbon steel differ both in mechanical and chemical properties. Several studies have been done to enumerate the capacity of stainless steel to satisfy structural demand in seismic excitation. Stainless steel contains more than 10.5% chromium and less than 1.5% carbon which makes it corrosion resistive. Again 8–10% nickel makes this material more ductile than mild steel [15]. Numerous studies proved the efficiency of SS-reinforced structure in seismic region. Zhang [16] focused on the impact of lateral loading on SS-reinforced bridge pier and found that stainless steel can resist the impact by dissipating energy under impact loading. A recent study conducted on local SS rebars shows that the bonding strength of SS is significantly good in concrete for both smooth and sand-coated steel [17]. The outcome of the study boosts the confidence of engineering community in using SS as rebar in concrete structures.

The chemical composition of the local SS rebar is presented in Table 1. The chemical composition of the stainless steel reflects that such properties and proportions of ingredients lie in 200 series SS (grade 201). Figure 1 shows the typical stress–strain curve for stainless steel and carbon steel. The carbon steel shows a defined sharp yield point, but stainless steel does not show any sharp yield point [18]. In order to investigate the mechanical properties of this local stainless steel rebars, tensile strength tests are conducted for few samples using Instron 8805,1000 kN hydraulic testing machine as shown in Fig. 2. Based on the tensile strength test data, the mechanical properties of SS rebar are presented in Fig. 3. The results show that the yield strength at 0.2% strength is 517 MPa with an ultimate strength of 728 MPa, whereas the strain at ultimate strength of the SS rebar is 18%. 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

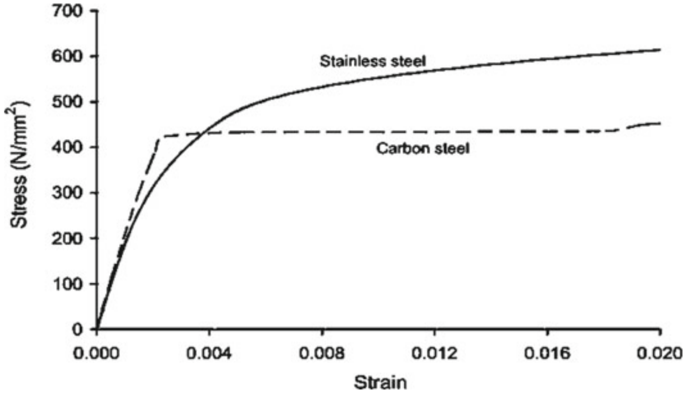

Fig. 1 Typical mechanical properties of carbon steel and stainless steel

Fig. 2 Test setups and failure modes of the samples [19]

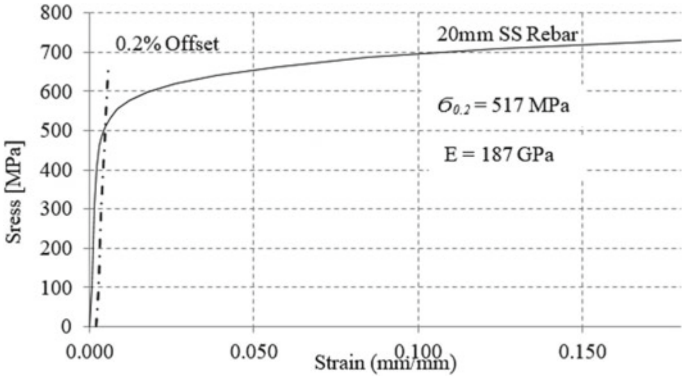

Fig. 3 Mechanical properties of the stainless steel grade 201

Previously, stainless steel was used because of its corrosion resistance. But nowadays for application in seismic region, it is becoming popular because of its remarkable ductile capacity. This paper assessed the comparative seismic performance of SS-reinforced bridge pier and carbon steel-reinforced bridge pier by performing nonlinear pushover analysis (NSPA). Different damage states are also developed according to code to understand the bridge piers functionality after an earthquake event.

2 Methodology

This section includes the geometric properties of the bridge pier, finite element modeling approach and performance-based bridge design and damage states under certain limit states. A standard bridge pier is selected for this study from existing literature [3] using AASHTO guideline [20]. The geometric features of the pier are presented below.

2.1 Geometry of Bridge Pier

In this section, the geometry of a bridge pier is described. For longitudinal and transverse reinforcement, stainless steel was used. This bridge needs to satisfy the purpose of a lifeline bridge to all traffic after an earthquake event with return period of 475 years. The studied bridge pier was designed considering a constant diameter of 1.6 m, the column was reinforced with 42 longitudinal stainless steel bars of 28 mm diameter with a reinforcement ratio of 1.4%, and 16 mm diameter stainless steel bars were used at 76 mm pitch. Aspect ratio 5 was selected which lead the height of the pier to be 8 m. The elevation and cross-sectional view of SS-reinforced bridge

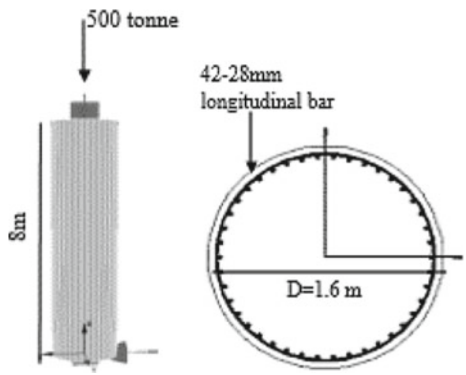

Fig. 4 Cross section and elevation of SS-reinforced concrete bridge pier

Table 2 Material properties

Material	Property	Values
Concrete	Compressive strength (MPa) Elastic modulus (GPa) Tensile strength (MPa) Strain	28 20.8 2.2 0.002
Stainless steel	Elastic modulus (GPa) Yield stress (MPa) Ultimate stress (MPa) Ultimate strain	187 517 728 0.18
Carbon steel	Elastic modulus (GPa)	207
	Yield stress (MPa)	550
	Ultimate stress (MPa)	621

is shown in Fig. 4. The other properties used in this study such as elastic modulus, yield stress and strain are given in Table 2.

Plastic hinge length for the pier was calculated by the equation prescribed by Paulay and Priestley [21] as shown in Eq. (1)

$$L_{\mathrm{p}} = 0.08L + 0.022d_{\mathrm{b}} f_y \quad (1)$$

where L = length of the member in mm; d_{b} = bar diameter in mm and f_{y} = yield strength of rebar in MPa.

For parametric study bridge pier of different yield strength, compressive strength and the longitudinal ratio were considered, and for every pier plastic hinge length was calculated with this equation.

2.2 *Finite Element Modeling*

The SS-reinforced bridge pier was modeled in finite element software SeismoStruct 2020. NSPA has been conducted to develop performance damage states of the bridge pier. This software is capable of predicting large displacement under both static and dynamic loads considering both geometric nonlinearities and material inelasticity. 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 conventional 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. The moment–curvature relationship for both the bridge piers is determined as shown in Fig. 5 and found to be comparable.

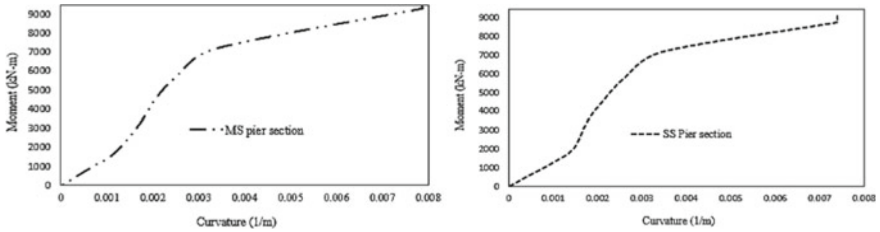

Fig. 5 Moment–curvature relationship of MS-RC and SS-RC bridge pier section

3 Performance-Based Damage States Criterion

Performance-based seismic design largely depends on the correlation between seismic performance levels and engineering damage states parameters. Among several damage states suggested by the researchers, three of them are commonly used, i.e., serviceability, damage control and life safety damages states [22]. Serviceability limit states say under seismic excitation, no damage repair is required and operation of the structure will not be hampered. Damage control indicates damage is repairable and operation is suspended while repairing. For life safety limit state, the structure will not collapse, but post-earthquake repairing is not possible. The performance objective depends on qualitative and quantitative parameters such as strain limits and drift. Depending on strain values of concrete and steel, four performance criteria have been considered here, the rebar concrete hairline cracking, yielding, concrete cover spalling and core concrete crushing. Under the serviceability limit, the structure is repairable, but reinforcing steel strain is limited to 0.015 for concrete structure [22]. For SS-reinforced bridge pier, the performance limits were considered based on the proposed damage states by [23]. Table 3 shows the damage states with their associated functional level.

Table 3 Performance criteria

Damage parameter	Damage state	Service	Performance description	Damage classification	Socioeconomic description
Cracking	DS-I	Immediate	Onset of hairline cracks	Minimal damage	Fully operational
Yielding	DS-II	Limited	Theoretical first rebar yield of longitudinal rebar	Repairable damage	Operational
Spalling	DS-III	Service disruption	Concrete spalling	Extensive damage	Life safety
Core crushing	DS-IV	Life safety	Crushing of core concrete	Probable replacement	Near collapse

The yielding of longitudinal SS rebar took place at tensile strain of steel which can be calculated as the ratio of yielding force and elastic modulus. Priestly (1996) recommended spalling strain of concrete to be 0.004. According to Kowalsky [24], crushing strain of confined concrete ranges between 0.015 and 0.05. For this paper, crushing strain of SS-RC bridge pier is calculated using the following Eq. (2) proposed by [24]

$$\varepsilon_{cu} = 0.004 + 1.4\rho_s f_{yh}\varepsilon_{su}/f_c' \quad (2)$$

where ε_{cu} = ultimate compression strain; ε_{su} = steel strain at maximum tensile stress; f_c' = concrete compressive strength in MPa; f_{yh} = yield strength of transverse steel in MPa and $\rho_{s=}$ volumetric ratio of confining steel.

Nonlinear pushover analysis was conducted to investigate the effect of flexural limit state on SS-RC bridge pier of different parameters. The pier will fail by concrete failure if the strain of concrete core reaches the ultimate strain (ε_{cu}). Failure will occur due to steel failure if the strain in steel rebar reaches to ultimate strain (ε_{su}).

4 Results and Discussions

4.1 Nonlinear Pushover Analysis

To understand the seismic vulnerability and inelastic behavior of the pier, nonlinear pushover analysis (NSPA) is an important step. In NSPA, the pier was subjected to incremental lateral load 1 m in form of displacement along with the axial load 500 tone in pier. From Fig. 6, it is observed that the SS-RC bridge pier shows ductile behavior [23]. At point A, the pier reaches the operation level of limit states, where damage is minimal and the seismicity has a probability of exceedance of 10% in 50 years with a return period of 475 years. Near collapse, state is reached at point B where extensive damage has been occurred under 2% probability of exceedance in 50 years with a return period of 2475 years according to Eurocode-8 [19]. In Fig. 7, it is found that both the OL and NC damage states are reached at an early stage in

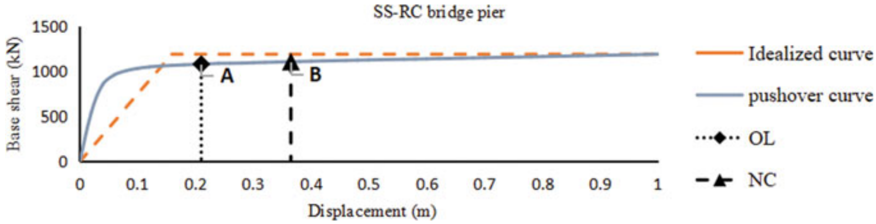

Fig. 6 Base shear versus target displacement for SS-RC bridge pier

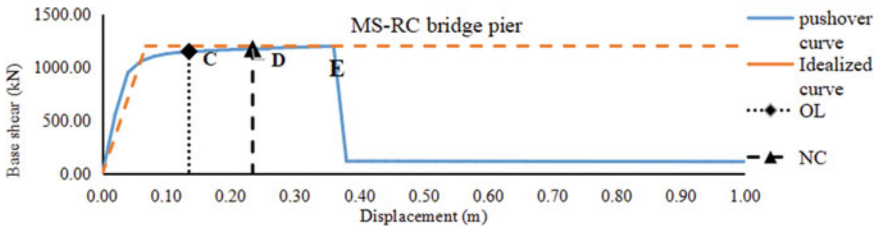

Fig. 7 Base shear versus target displacement for MS-RC bridge pier

case of MS-RC bridge pier. The pier could not sustain the lateral load increment and collapsed at point E with 0.36 m displacement.

4.2 Comparison of Performance Damage States Between MS-RC and SS-RC Bridge Pier

Behavior mode assessment is important to observe the seismic response of a structure. Depending on lateral deformation, structure can be classified as brittle, strength degradation and ductile [23]. For defining serviceability, damage control states of bridge pier displacement evaluation are important rather than forces. Therefore, Priestley [25] has also given emphasize on displacement-based design approach for seismic response evaluation in their researches. According to Federal Emergency Management Agency (FEMA) [26], two performance ranges are defined in Figs. 8 and 9. The damage control stage covers elastic range of structure, where the damage is low and repairing cost is also minimum. In Fig. 8, it can be seen that MS-RC bridge pier shows brittle behavior, and damage control state is limited to yielding and cracking stage.

SS-RC bridge pier in Fig. 9 is showing more ductile behavior than MS-RC bridge pier, and damage control state ranges up to spalling stage with larger lateral deformation. Among four limit states, cracking occurs at same displacement for both pier,

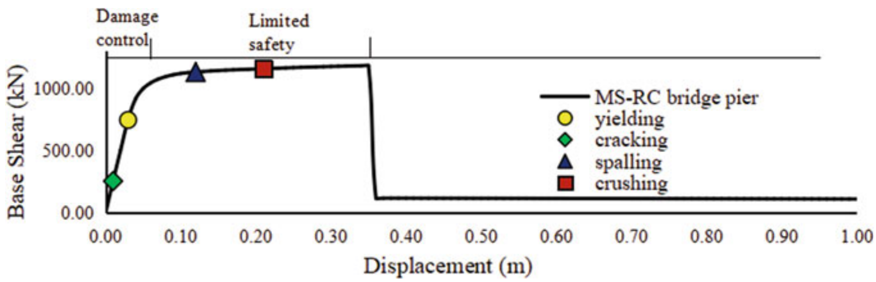

Fig. 8 Pushover curve showing damage states for MS-RC bridge pier

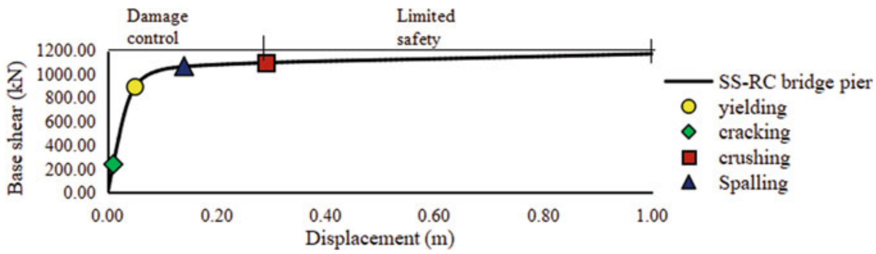

Fig. 9 Pushover curve showing damage states for SS-RC bridge pier

yielding has increased displacement up to 40%, spalling and crushing have displacements of 14.3 and 27.6%, but the base shear decreases to 6.5, 5.4 and 5% in case of cracking, spalling and crushing, whereas 16.5% base shear increases for yielding in case of SS-RC bridge pier. In limited safety range, large deformation and damage may occur which causes significant risk of life and economic losses. Stainless steel enhances the ductile capacity of the pier by allowing the pier to achieve higher yielding, and therefore by dissipating more energy, it can reduce the probability of failure.

4.3 Parametric Study

The performance of the bridge pier can be estimated in terms of different limit states by defining corresponding strain limits. In order to observe the effect of different parameters of SS-RC bridge pier, four performance criteria have been considered: the cracking, yielding, spalling and crushing of concrete and longitudinal steel as stated in the previous section. In Table 4, three parameters are selected to conduct the NSPA to see the influence of variable parameters on the pier. Table 5 shows the different pier properties used in the analysis.

All the parameters affect the flexural performance of the pier substantially. The higher value of the parameters increase the capacity of the piers. In Fig. 10, it is observed that for 42.4 MPa concrete strength yielding and cracking occur at higher values of base shear 17.6% and 16.5%, respectively, while the base shear of spalling and crushing increases by 5 and 4.2% compared to 28 MPa. Compressive strength

Table 4 Details of variable parameters used in the study

Variable parameter	Value		Unit
	Level-1	Level-2	
Compressive strength of concrete, f_c'	28	42.4	MPa
Yield strength of steel, f_y	517	748	MPa
Longitudinal steel reinforcement ratio, ρ_L	1.4	1.7	%

Table 5 Details of SS-RC bridge pier

Variable	Pier-ID	f_c'(MPa)	f_y (MPa)	ρ_L(%)
Compressive strength of concrete, f_c'	P-1–28 P-1–42.4	28 42.4	748 748	1.7 1.7
Yield strength of steel, f_y	P-2–517 P-2–748	42.4 42.4	517 748	1.4 1.4
Longitudinal steel reinforcement ratio, ρ_L	P-3–1.4 P-3–1.7	28 28	517 517	1.4 1.7

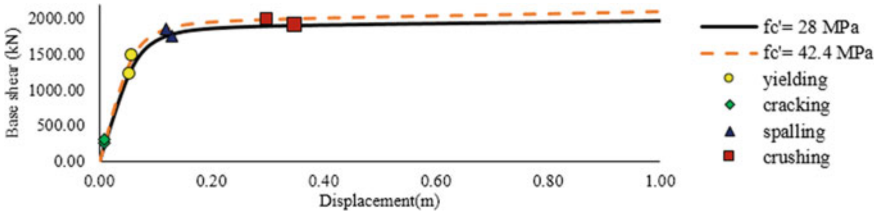

Fig. 10 Pushover curve considering variable compressive strength of concrete

28 MPa decreases displacement at yield state by 16% while cracking occurs at same displacement, but in spalling and crushing states, the displacement increases by 7.7 and 14.2%. Low compressive strength has low modulus of elasticity which lead the pier to achieve more deformability and causes higher displacement. The pier exhibits lower stiffness at low compressive strength and thus shows more effectiveness than high strength concrete.

Figure 11 shows how the variable yield strength affects the flexural capacity of bridge pier. It is seen that the higher yield strength (748 MPa) increases value of base shear significantly. Four limit states cracking, yielding, spalling and crushing have base shear increment of 1.7%, 24.3%, 20.5% and 27.6%, and larger displacement by 16.7%, 6.7% and 3.2% for yielding, spalling and crushing, respectively, but displacement in concrete cracking is found similar compared to lower yield strength of steel 517 MPa.

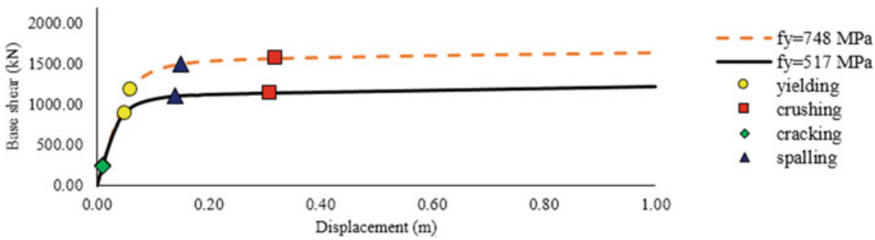

Fig. 11 Pushover curve considering variable yield strength of steel

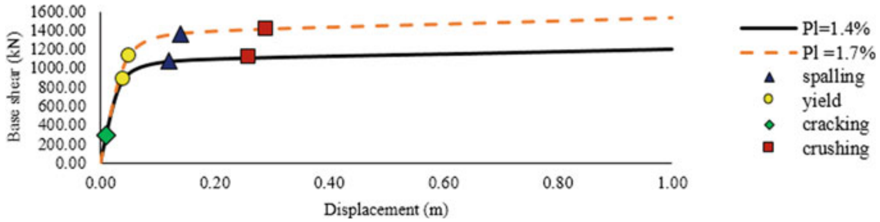

Fig. 12 Pushover curve considering variable steel reinforcement ratio

In Fig. 12, it is observed that longitudinal reinforcement ratio influences the base shear capacity of pier substantially. For cracking, yielding, spalling and crushing, the base shear is improved by 1.5, 22, 20.5 and 21.3% for 1.7% reinforcement ratio. The displacement is increased by 20% for yielding, 14.2% for spalling and 10.3% for crushing states compared to 1.4% steel ratio. Higher steel ratio influences the pier stiffness considerably.

5 Conclusion

In order to develop performance-based seismic design, it is important to define flexural limit states in a structure. Nonlinear pushover analysis is performed on the actual bridge pier to evaluate the damage states in terms of base shear and displacement. From the study, it is seen that the SS-RC bridge pier can sustain seismic excitation effectively by ductile structural behavior and higher energy absorption capacity. Though the pier shows more lateral displacement, it provides better performance under lateral load and resists the structure from brittle failure. Post-earthquake loss of life and structural damage are lesser in case of the SS-RC bridge pier. SS-RC pier controls the damage up to near collapse limit state for its ductile mode of behavior. The pier remains operational, and less repair is required under this damage control state.

In case of MS-RC bridge pier, it is found that at a lower drift value, the structure behaves more brittle and collapses under lateral load increment. This phenomenon is not desirable for any designer to build structure in seismic zone. Moreover, the yielding of longitudinal reinforcement occurs at an early stage in case of carbon steel which may not be the true representative of ductile behavior. In this regard, stainless steel shows more resilient characteristics by yielding in higher displacement and lower base shear. From the parametric study, it is observed that a higher value of different parameters can increase the SS-RC bridge pier capacity considerably. As an example, with a compressive strength of 42.4 MPa, the base shear increases at yielding, cracking, spalling and crushing limit states by 17.6%, 16.5%, 5% and 4.2%, respectively. A higher value yield strength (748 MPa) results higher base shear for all four limit states by 24.3, 1.7, 20.5 and 27.6%. High steel ratio (1.7%) improves the base shear capacity by 22, 1.5, 20.5 and 21.3% compared to that of 1.4% steel.

It can be concluded from the investigation that stainless steel can be used as rebar in concrete structure as it is more preferable for application in the seismic region for its exceptional ductile behavior and inherent corrosion resistivity. Using stainless steel in bridge pier can reduce the long-term maintenance cost and economic loss under strong ground motion. Moreover, its energy dissipation capacity is higher than conventional carbon steel which will certainly make it more popular to build a sustainable structure. To obtain the desired damage state and to keep the bridge operational after an earthquake event, stainless steel rebars can make a difference.

References

1. Priestley, M.J.N.: Performance based seismic design. Bull. N. Z. Soc. Earthq. Eng. **33**(3), 325–346 (2000). https://doi.org/10.5459/bnzsee.33.3.325-346
2. Sheikh, M.N., Légeron, F.: A checking method for multiple seismic performance objectives of bridge piers designed according to code provisions. J. Earthq. Eng. **20**(7), 1148–1168 (2016). https://doi.org/10.1080/13632469.2015.1118709
3. Muntasir Billah, A.H.M., Shahria Alam, M.: Performance-based seismic design of shape memory alloy-reinforced concrete bridge piers. I: development of performance-based damage states. J. Struct. Eng. (United States), **142**(12) (2016). https://doi.org/10.1061/(ASCE)ST.1943-541X.0001458
4. Cassese, P., De Risi, M.T., Verderame, G.M.: Seismic assessment of existing hollow circular reinforced concrete bridge piers. J. Earthq. Eng., 1–36 (2018). https://doi.org/10.1080/13632469.2018.1471430
5. Parghi, A.M.: Seismic performance evaluation of circular reinforced concrete bridge piers retrofitted with fiber reinforced polymer. Researchegate.net (2016). https://doi.org/10.14288/1.0308726
6. Al-Hussaini, T.M., et al.: New dynamic testing facility at BUET-JIDPUS: cyclic loading of 1/3 scale damaged RC column retrofitted with externally wrapped CFRP sheets. In: 15th International Conference on Structural and Geotechnical Engineering. Egypt
7. Pang, Y., Li, L.: Seismic collapse assessment of bridge piers constructed with steel fibers reinforced concrete. PLoS ONE **13**(7) (2018). https://doi.org/10.1371/journal.pone.0200072
8. Farzana, K., Ahmed, K.: Performance based seismic analysis of stainless steel reinforced concrete bridge pier using damping ductility relationship. In: Adavnce in Bridge Engineering IABSE.
9. Tabassum, T., Ahmed, K.S.: Improving lateral load bearing capacity of RC buildings using non-linear dampers. Int. J. Sci. Technol. **46**(1), 31–40 (2018)
10. Ahmed, K.S., et al.: Seismic performance investigation of base isolation system for typical residential building in Bangladesh. Adv. Civ. Infrastruct. Constr. Mater. **4**(1) (2016)
11. Mahmud, R., Ahmed, K.S.: Interface dependency of reinforced concrete jacketing for column strengthening. Struct. Build. **173**(1), 31–41 (2020). https://doi.org/10.1680/jstbu.17.00124
12. Melo, J., Afshan, S., Rossetto, T., Varum, H.: Experimental investigation of cyclic response of stainless-steel reinforced concrete columns. In: Proceedings of the SECED 2019 Conference: Earthquake Risk and Engineering towards a Resilient World. SECED: London, UK., (September), pp. 1–9 (2019)
13. Zhou, Y., Ou, Y.-C., Lee, G.C., O'connor, J.S.: A pilot experimental study on the low cycle fatigue behavior of stainless steel rebars for warthquake engineering applications. Masters Abstr. Int. **47**(1) (2008)

14. Franchi, A., Crespi, P., Bennani, A., Farinet, M.: Stainless steel rebar for seismic applications. Solid Mech. Its Appl. **140**, 255–264 (2006). https://doi.org/10.1007/1-4020-4891-2_21
15. Gardner, L.: The use of stainless steel in structures. Prog. Struct. Eng. Mater. (2005) https://doi.org/10.1002/pse.190
16. Zhang, G., Xu, S., Xie, H., Zhou, X., Wang, Y.: Behavior of stainless steel-reinforced concrete piers under lateral impact loading. Adv. Mech. Eng. **9**(5) (2017). https://doi.org/10.1177/1687814017709936
17. Islam, K., et al.: Exploratory study on bond behavior of plain and sand coated stainless steel rebars in concrete. Structures. **27**, 2365–2378 (2020). DOI: https://doi.org/10.1016/j.istruc.2020.07.039
18. Liao, F.-Y., Han, L.-H., Tao, Z., Rasmussen, K.J.R.: Experimental behavior of concrete-filled stainless steel tubular columns under cyclic lateral loading. J. Struct. Eng. **143**(4), 04016219 (2017). https://doi.org/10.1061/(asce)st.1943-541x.0001705
19. Ahmed, K.S., Habib, M.A., Asef, M.F.: Flexural response of stainless steel reinforced concrete beam. Structures **34**, 589–603. https://doi.org/10.1016/j.istruc.2021.08.019 (2021)
20. Officials, T.: AASHTO guide specifications for LRFD seismic bridge design. In: Transportation, (May), 1 v. (loose-leaf) (2011). https://doi.org/10.2337/dc12-1714
21. Paulay,T., Priestley, M.N.J.: Seismic Design of Reinforced Concrete and Masonry Buildings. Willey, NewYork (1992)
22. Kowalsky, M.J.: Deformation limit states for circular reinforced concrete bridge columns. J. Struct. Eng. New York, N.Y. **126**(8), 869–878 (2000). https://doi.org/10.1061/(ASCE)0733-9445(2000)126:8(869)
23. Hose, Y., Silva, P., Seible, F.: Development of a performance evaluation database for concrete bridge components and systems under simulated seismic loads. Earthq. Spectra. **16**(2), 413–442 (2000). https://doi.org/10.1193/1.1586119
24. Kowalsky, M.J., Priestley, M.J.N., MacRae, G.A.: Displacement-based design of RC bridge columns in seismic regions. Earthqu. Eng. Struct. Dynam. **24**(12), 1623–1643 (1995). https://doi.org/10.1002/eqe.4290241206
25. Priestley, M.J.N., Calvi, G.M., Kowalsky, M.J.: Displacement-based seismic design of bridges. In: Bridge Engineering Handbook: Seismic Design, 2nd edn, pp. 201–236. CRC Press (2014). https://doi.org/10.1201/b15663
26. FEMA 356: FEMA 356—Prestandard and Commentary for the Seismic Rehabilitation of Buildings, Federal Emergency Management Agency. Report FEMA-356, Washington, DC (2000). Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Prestandard+and+commentary+for+the+seismic+rehabilitation+of+buildings#0
27. Kolias, B.: Eurocode 8—part 2. Seismic design of bridges. In: Eurocodes: Background and Applications, p. 20. Brussels (2008). Retrieved from http://eurocodes.jrc.ec.europa.eu/showpage.php?id=332