Seismic Assessment of Concrete Column Reinforced with Fiber Reinforced Polymer and Stainless Steel Rebars

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Abstract: The fiber reinforced polymer (FRP) rebar is utilized as a corrosion resistive reinforcement in the structural elements like a beam, column, and slab. The FRP rebar offers excellent mechanical and durability properties, like high strength to weight ratio, high stiffness, and corrosion resistance to structures. However, a lower ductility subjected to linear-elastic behaviour, and the brittle nature of FRP particularly in the case of column applications is getting attention among researchers. Whereas stainless steel (SS) having adequate ductility, low maintenance, and resistance to corrosion make it an ideal material for reinforcing applications. To improve the performance of FRP-reinforced elements and diminish the brittle behaviour, the present research is focused on the utilization of SS rebar in the plastic hinge region of the column along with FRP rebar in rest portion of a column. This hybrid configuration is adopted here to improve the ductility and corrosion resistance capacity of the RC column. The damage concentration of the hybrid column is analysed under the effect of nonlinear static loads. The parametric analysis is performed over the hybrid column to study the behaviour of different factors under pushover loading. The results indicate that the ductility of the SS-FRP RC column is achieved under seismic loads. The study reveals that axial load, the yield strength of steel and aspect ratio significantly affect the behaviour of the SS-FRP RC column.

1. Introduction
In the past few years, the seismic design guidelines are aiming at the performance-based design to forecast well-accomplished structural conditions and the post-earthquake functionality. The main goal of the present design concepts is to confirm that the failure of a structure is prohibited, and there is no need to limit the loss of post-seismic action retrieval. As per the modern philosophies of seismic design, a structure is predicated on suffering fatalities under the optimized predictable seismic force. However, the structure does not fail or collapse completely, and it will limit the substantial damages for post-seismic action retrieval [1]. Hence, the current advancement in performance-based seismic assessment and design approach is emphasized to define and evaluate the permanent damages of a structure caused after the occurrence of massive earthquakes. During a seismic event, the longitudinal members of a column perform as a critical member of the frame structure to resist the seismic forces. In the recent earthquakes, the majority of structures were collapsed due to the poor performance of critical column sections. The maximum damage of a column is concentrated in the bottom region, defined is the plastic hinge region of a column.
Corrosion is the main factor that decreases the service life and long-term durability of RC structures. Several methods are adopted in order to minimize the corrosion and increase the endurance of the RC structures, such as fusion bonded epoxy (FBE) powder coatings and linings, cathodic and anodic coating, claddings, corrosion resistance alloys, and utilization of corrosion resistive SS composites. In RC structures, SS is utilized as a reinforcing material at seaside areas to prevent initial corrosion. In India, Europe, and North America, several bridges were built and repaired using SS for its corrosion resistance compared to conventional steel. The federal highway administration (FHWA) [2] has reported that SS bars are proficient at providing a complete service life of structures once the concrete becomes worsened. The field applications have unveiled that the utilization of SS rebar raises the total expenditure of a structure by 3% [3]. Additionally, SS rebar having adequate ductility, low maintenance, and resistance to corrosion make it an ideal material for the reinforcing applications. Hence, to diminish the overall cost and to increase the resistance from corrosion, FRP rebar is a suitable substitute for conventional reinforcement in the construction industry [12].

FRP is composed of mixing the fiber and resin and cured at room temperature afterward. In RC structures, rebar gets corroded due to de-salting, seawater, and natural factors like the freeze-thaw cycles [4]. FRP composite material can be utilized as a reinforcing material because of several characteristics of FRP, such as high stiffness and strength, corrosion-resistance, less weight, and easy to install [5]. Moreover, FRP rebar is utilized in civil engineering applications, e.g., RC buildings, bridges, etc. There are four main types of FRP, defined as glass (GFRP), basalt (BFRP), aramid (AFRP) and carbon (CFRP). Amongst these types, GFRP is the most utilized in civil engineering applications. The use of a polymeric matrix protects the surface and binds the fibers during manufacturing, transportation, handling, and throughout the service life of composite bars. Since polymeric matrix transfers the stresses to the fibers throughout the form, it should exist with the fibers in terms of its chemical and thermal properties. The commonly used resins are vinyl esters, epoxy, and polyester [6].

The main goal of this research is to examine the seismic behavior of joined RC columns reinforced with SS rebars in the plastic hinge region, and FRP rebars in the remaining part of a column. The performance of SS-FRP is evaluated in terms of base shear, displacement, and ductility.

2. Research Significance
In the present study, the effectiveness of SS-FRP hybrid reinforcement in RC columns is evaluated in order to improve the durability and seismic performance. Though FRP-reinforced structures can diminish the issues related to corrosion of steel, stiffness and compressive strength of FRP rebars make structures more susceptible to instability. ACI 440.1R-2006 [7] has recommended not to use the FRP bar as longitudinal reinforcement in flexural members (columns) because of the unavailability of adequate experimental support evidence. However, studies in the last few years reveal that the behavior of FRP-reinforced structures was found to be similar to the steel-reinforced structures [8]. While ductility can be incorporated in the design of FRP-RC, they will not only be extremely corrosion-resistant but also capable of dispersing significant energy during the earthquakes.

In this study, a hybrid SS-FRP configuration of reinforcement is incorporated to enhance the resistance to high corrosion in RC columns. Conventional steel is not used as an optimal solution to corrosion problems, whereas SS and FRP are likely to be considered to improve the performance of RC columns. Replacing SS rebar with conventional steel rebar in the plastic hinge regions increases the adequate ductility of columns, and utilizing FRP rebar in the remaining regions prevents the RC columns from corrosion. Generally, the unrecoverable deformation was observed in structural columns, as they are more vulnerable to severe damages subjected to enormous seismic energy. This study aims to indicate that the adequate ductility of the SS-FRP RC column is achieved under seismic loads.
3. Constitutive Material Model

The concrete is modeled utilizing a uniaxial nonlinear constant confinement model, developed by Madas [9], following the constituent framework suggested by Mander et al. [10] and the cyclic guidelines proposed by Martenize Rueda and Elnashai [11]. Mander et al. [10] proposed guidelines for the incorporation of confinement effects provided by the lateral transverse reinforcement, where the stress-strain range is assumed constant confining pressure is assumed throughout the entire stress-strain range. Five concrete material properties are used in Mander et al. [10] for the required calibration of a model. The input parameters and values are compressive strength \( (f'_c = 38.30 \text{ MPa}) \), mean tensile strength \( (f_t = 3.33 \text{ MPa}) \), modulus of elasticity \( (E_s = 23.1 \text{ GPa}) \), Strain at peak stress \( (\varepsilon_c = 0.0029 \text{ m/m}) \), and specific weight \( (\gamma = 24 \text{ kN/m}^3) \) [12].

SS possesses a bilinear uniaxial stress-strain \( (\sigma - \varepsilon) \) model by kinematic strain hardening, and it remains constant throughout the elastic limit at the different loading stages. The kinematic hardening regulation for the surface of yield is predicated as a linear function of the plastic strain increase. This type of simple model is also characterized by easily distinguishable rectifying factors and through its computational efficacy. Four SS material properties are used in bilinear uniaxial \( \sigma - \varepsilon \) for the required calibration of a model. The parameters and properties of bilinear steel are elastic modulus \( (E_s = 19 \text{ GPa}) \), yield strength \( (f_y = 402 \text{ MPa}) \), specific weight \( (\gamma = 24 \text{ kN/m}^3) \) and strain hardening parameter \( (\mu = 0.0125) \) are used in this model.

FRP was modeled as a generalized uniaxial elastic material system with a compression and tension specific elastic modulus. The different factors are utilized to determine the material in this model, e.g. elastic modulus \( (E_s = 52.2 \text{ GPa}) \), ultimate compressive strength \( (f'_c u = 728 \text{ MPa}) \), and ultimate tensile strength of FRP bar \( (f_{FRP,u} = 364 \text{ MPa}) \).

4. Design and Geometry of the SS-FRP RC Column

The detailed section, longitudinal reinforcement, and configuration of the SS-FRP RC column are adopted from Billah and Alam [12]. The detailed geometry of RC column is shown in Figure 1, shows the distribution of longitudinal reinforcement for SS-FRP columns, which has a square cross-section of \( 450 \times 450 \times 3200 \text{ mm} \), reinforced with M-20 grade concrete, 19.5 mm diameter of SS bar, 19.5mm diameter of FRP longitudinal rebars. The gross reinforcement ratio is 1.2 percent.

![Figure 1. Geometry of Hybrid RC column](image-url)

The investigators have recognized the effect of concrete strength on the plastic hinge length of RC members [12]. The equations of plastic hinge length given by most of the design codes and investigators do not consider the effect of the concrete strength. Though the influence of concrete strength is known only by the plastic hinge definition suggested by Billah and Alam [13], we have
observed the increment in concrete strength as plastic hinge length decreases, as evident from their equation of plastic hinge length. The following equation 1 is utilized to compute the plastic hinge length, according to Paulay and Priestley [14].

\[ l_p = 0.081 + 0.022d_b f_y \]  

Where \( l_p \) = plastic hinge length, \( d_b \) = diameter of rebar (mm), \( f_y \) = yield strength of rebar (MPa)

5. Hybrid Rebar Connection
There are different categories of mechanical couplers utilized in the RC structures to connect smooth and deformed rebars. Yet modern splicing methodology is not appropriate for splicing varying genera of rebars. The connection of SS and FRP rebars involves economic, easy and effective techniques to empower the use of SS in sensitive positions of RC structures. For the splicing these rebars, screw lock-adhesive type couplers are used, as it does not require any assembly equipment and achieve speedy construction. Alam et al. 2010 [15] performed numerous experiments and developed a mechanical-adhesive style coupler. Using multi-row flat screws, the SS bar was connected to the coupler in one part, while the FRP bar was connected to a SS bar by epoxy on the other part.

6. Validation of Numerical Analysis
The column was designed and analytically tested under nonlinear static pushover loading defined by Billah and Alam [12]. The performance of the column applied nonlinear static pushover loading in relationships of tip load versus displacement. The applied load was displacement controlled along with 400 kN axial gravity loading. A numerical model in this investigation is validated using anon-linear FE software tool [16]. The hybrid column is modeled utilizing SS reinforcement in the plastic hinge region, and FRP reinforcement in the remaining length of a column. The columns are analyzed under the effect of nonlinear static pushover loads. Figure 2 portrays the comparison of predicted base shear versus displacement of the numerical model with experimental results by Billah and Alam [12]. It has been seen from Figure 2 that the numerical model with the adopted modeling techniques is verified with the actual empirical-numeric results with accuracy.

![Base Shear-Displacement Curve](image)

**Figure 2.** Validation of pushover analysis SS-FRP hybrid column with existing literature

7. Finite Element (FE) Modeling of SS-FRP RC Column
The finite element (FE) based program such as Seismo Struct [16], is adopted in the present study to analyse the seismic performance of the SS-FRP RC column. This program can predict large displacement behavior of the structure and is able to consider both material inelasticity and geometric non-linearity. The methodology of fiber modeling is used to describe the distribution of material nonlinearity along with the length of member and cross-section of the component. A bond-slip link is incorporated in the analytical model to join the hybrid RC column, which is signified by rotational
spring at joint. A constant 400 KN axial load is applied at the top of a column to simulate the gravity loads.

A displacement-based nonlinear beam-column element is chosen for the RC column. The fiber section is used to discretize pier into three parts: core fiber for confined concrete, cover fiber for unconfined concrete, and steel fiber for reinforcement bars. The piers are modeled using a force-based inelastic system owing to its accuracy. The pier length is divided into a total of 11 sections, among which three sections represent plastic hinge length, and the remaining sections represent SS rebar[12]. After the successful validation of a numerical model with literature, this study is extended for the performance analysis. Various factor-like axial load, compressive strength of concrete, yield strength of steel, and aspect ratio are considered for the parametric study. Details of parameter and corresponding terms are shown in Table 1.

| Parameter                  | Column ID | Load (kN) | l/d | f_c (MPa) | Axial load (%) | fy (MPa) | d (mm) | l (mm) | lp (mm) |
|----------------------------|-----------|-----------|-----|-----------|----------------|----------|--------|--------|---------|
| Aspect ratio, l/d          | P-1-7.5   | 400       | 7.5 | 38.3      | 10             | 402      | 450    | 3375   | 442     |
|                            | P-2-8.5   | 400       | 8.5 | 38.3      | 10             | 402      | 450    | 3825   | 478     |
|                            | P-3-9.5   | 400       | 9.5 | 38.3      | 10             | 402      | 450    | 4275   | 514     |
| Compressive strength, f_c  | P-1-35    | 400       | 7.1 | 35.0      | 10             | 402      | 450    | 3200   | 428     |
|                            | P-2-45    | 400       | 7.1 | 45.0      | 10             | 402      | 450    | 3200   | 428     |
|                            | P-3-55    | 400       | 7.1 | 55.0      | 10             | 402      | 450    | 3200   | 428     |
| Axial load, P              | P-1-5.0   | 200       | 7.1 | 38.3      | 5              | 402      | 450    | 3200   | 428     |
|                            | P-2-7.5   | 300       | 7.1 | 38.3      | 7.5            | 402      | 450    | 3200   | 428     |
|                            | P-2-12.5  | 500       | 7.1 | 38.3      | 12.5           | 402      | 450    | 3200   | 428     |
| Yield strength, fy         | P-1-250   | 400       | 7.1 | 38.3      | 10             | 250      | 450    | 3200   | 363     |
|                            | P-2-450   | 400       | 7.1 | 38.3      | 10             | 550      | 450    | 3200   | 449     |
|                            | P-2-650   | 400       | 7.1 | 38.3      | 10             | 650      | 450    | 3200   | 535     |

8. Results and Discussion

The results of the numerical parametric analysis are described in Table 2. It can be observed that the aspect ratio (l/d), axial load (P), compressive strength of concrete (f_c), and yield strength of steel (fy) are significantly affecting the maximum base shear and top displacement of SS-FRP RC columns.

| Parameter                  | Column ID | Cracking | Yielding | Crushing | Maximum |
|----------------------------|-----------|----------|----------|----------|---------|
|                            |           | Base Shear (kN) | Disp. (mm) | Base Shear (kN) | Disp. (mm) | Base Shear (kN) | Disp. (mm) | Base Shear (kN) | Disp. (mm) |
| Aspect Ratio               | P-1-7.5   | 29.45    | 6.0      | 43.41    | 24       | 69.72    | 186       | 73.01       | 108      |
|                            | P-2-8.5   | 25.86    | 8.0      | 36.04    | 28       | 55.35    | 244       | 61.12       | 128      |
|                            | P-3-9.5   | 22.22    | 8.0      | 31.65    | 36       | 42.73    | 316       | 51.54       | 148      |
| Axial Load                 | P-1-5.5   | 28.09    | 3.0      | 33.63    | 18       | 75.15    | 171       | 78.54       | 300      |
|                            | P-2-7.5   | 25.22    | 3.0      | 41.07    | 21       | 75.59    | 168       | 76.22       | 123      |
|                            | P-3-12.5  | 35.31    | 6.0      | 50.82    | 21       | 77.01    | 159       | 81.16       | 90       |
| Compressive strength       | P-1-35    | 25.02    | 3.0      | 45.62    | 21       | 69.98    | 255       | 77.95       | 99       |
|                            | P-2-45    | 23.43    | 3.0      | 76.93    | 21       | 79.05    | 153       | 79.18       | 102      |
|                            | P-3-55    | 26.86    | 3.0      | 79.85    | 18       | 82.19    | 147       | 81.08       | 102      |
| Yield strength of steel    | P-1-250   | 24.99    | 3.0      | 45.03    | 21       | 56.90    | 153       | 59.52       | 75       |
|                            | P-2-450   | 25.11    | 3.0      | 46.36    | 21       | 82.32    | 168       | 81.09       | 96       |
|                            | P-3-650   | 25.23    | 3.0      | 47.50    | 21       | 107.66   | 183       | 75.72       | 300      |
The l/d ratio substantially decreases the value of maximum base shear as the aspect ratio increases from 7.5 to 9.5. Corresponding top displacements increase with an increase in the l/d ratio from 7.5 to 9.5. The axial load significantly decreases the value of maximum base shear as axial load increases from 5 to 7.5. Further, increase the amount of maximum base shear with increase the axial load. Corresponding top displacements decrease with an increase in axial load from 5 to 7.5. The f′c is significantly increasing the value of maximum base shear as f′c increases from 35 to 55. Corresponding top displacements increase with an increase in f′c from 35 to 55. The fy of steel firstly decreases the value of maximum base shear as the fy of steel at 250. Further reduces the amount of maximum base shear with increase the fy of steel. Corresponding top displacements increase with an increase in fy of steel from 250 to 650. As described in Table 2 and Figure 3, the aspect ratio (l/d) of 7.5 shows higher base shear values for cracking, yielding and crushing as compare to an aspect ratio of 8.5 by 12.19, 16.98 and 20.61 %, respectively. The aspect ratio of 7.5 shows lower values of displacement for cracking, yielding and crushing as compared to an aspect ratio of 8.5 by 25, 14.28 and 22.54 %, respectively. Also, the l/d ratio of 8.5 shows the higher base shear value for cracking, yielding and crushing as compare to an l/d ratio of 9.5 by 14.07, 12.18 and 22.80 %, respectively. The l/d ratio of 8.5 shows lower values of displacement for cracking, yielding and crushing as compared to an l/d ratio 9.5 by 0, 22.22 and 22.78 %, respectively.

As described in Table 2 and Figure 4, the axial load (P) of 5 shows the higher base shear value for cracking compared to the axial load of 7.5 by 10.22. The axial load of 5 shows the lower base shear value for yielding and crushing as compare to the axial load of 7.5 by 18.12 and 0.58, respectively.
The axial load of 5 shows the same, lower and higher value of displacement for cracking, yielding and crushing as compared to axial load of 7.5 by 0.00, 14.29 and 1.75 %, respectively. Also, the axial load of 7.5 shows the higher base shear value for cracking, yielding and crushing as compare to an axial load of 12.5 by 28.58, 19.19 and 01.84 %, respectively. The axial load of 7.5 shows lower, same and higher value of displacement for cracking, yielding and crushing as compare to an axial load of 12.5 by 50, 0.0 and 5.06 %, respectively.

As described in Table 2 and Figure 5, the compressive strength of concrete, (f’c) of 55 shows higher base shear values for cracking compared to the f’c of 45 by 6.35. The f’c of 35 shows lower base shear values for yielding and crushing as compared to the f’c of 45 by 40.70 and 11.47, respectively. The low f’c strength of 35 shows the same, lower and higher values of displacement for cracking, yielding and crushing as compare to f’c of 45 by 0, 61.11 and 40.00 %, respectively. Also, the effect f’c of 45 shows lower base shear values for cracking, yielding and crushing as compare to f’c of 55 by 12.77, 3.66 and 3.82 %, respectively. The f’c of 45 shows the same, same and higher values of displacement for cracking, yielding and crushing as compare to the f’c of 55 by 0.00, 0.00 and 03.92 %, respectively.

As described in Table 2 and Figure 6, The yield strength of steel (f’y)250 shows higher base shear values for cracking, yielding and crushing as compared to f’y of 450 by 0.47, 2.85 and 30.88 %, respectively. The fy of 250 shows the same, same and lower values of displacement for cracking, yielding and crushing as compare to fy of 450 by 0.0, 0.0 and 8.93 %, respectively. Also, the fy of 450 shows the lower base shear value for cracking, yielding and crushing as compare to fy of 650 by 0.476, 2.40 and 23.54 %, respectively. The fy of 450 shows the same, same and lower values of displacement for cracking, yielding and crushing as compare to fy of 650 by 0.00, 0.00 and 8.20 %, respectively.

In terms of ductility, the performances of different types of columns with variable parameters are also compared. In evaluating performance and evaluating seismic design forces during an earthquake event, structural ductility plays an important role. As well as ductility is also a contributing factor for structures to evaluate the capacity of energy dissipation. Ductility is defined as the ratio of ultimate displacement (µd) to yield displacement, which is a dimensionless variable. The displacement of yield corresponds to the first yielding of tension reinforcement. Various investigators have revealed the final movement in a different way. Numerous researchers and nearly all the design guidelines (FEMA 440) [17] have identified the ultimate displacement as the maximum displacement corresponding to optimum base shear. The final movement in this study is the displacement corresponding to a load falling from the peak load. Figure 7 shows the variation in ductility for various hybrid RC columns. The ductility is decreased from 12 to 8, with an increase in the aspect ratio from 7.5 to 9.5. Similarly, the same observation was observed in case of axial load, where 5 % axial load possesses the ductility value of 17, and 12.5 % axial load possesses the ductility value of 12, and 7.5 % axial load ratio possesses the ductility value of 14.

![Figure 7. Ductility of FRP-SS columns](image-url)
9. Conclusions
The study was carried out through inelastic pushover analysis on corrosion-free SS-FRP RC columns for seismic investigation of the RC column, where stainless steel is used in the plastic hinge region and FRP in another area of the column. The results of the SS-FRP RC column in terms of base shear vs. displacement are validated with existing literature. Based on the numerical study, under the seismic excitations, using SS in the plastic hinge zone improved the seismic behaviour of the columns significantly. Based on the numerical parametric analysis are significantly affecting the maximum base shear and displacement of SS-FRP RC column, the following result can be obtained.

- It is observed that with increases in the aspect ratio substantially decreases the value of maximum base shear.
- The aspect ratio (l/d) of 7.5 shows the higher base shear value for cracking, yielding and crushing as compare to an aspect ratio of 8.5 by 12.19, 16.98 and 20.61 %, respectively.
- The axial load ratio of 5 shows a higher base shear value for cracking compare to an axial load ratio of 7.5 by 10.22.
- The higher compressive strength of concrete (f\(_c\)) of 55 show higher base shear value for cracking compare to the lower compressive strength of concrete of 45 by 6.35.
- The lower yield strength of steel (f\(_y\)) 250 shows the higher base shear value for cracking, yielding and crushing as compare to higher yield strength of steel of 450 by 0.47, 2.85 and 30.88 %, respectively.
- The aspect ratio and axial load are the most significant factors for the ductility of the SS-FRP RC column.
- The results indicate adequate ductility of the SS-FRP RC column is achieved under seismic loads.
- The study reveals that the axial load (P), yield strength of steel (fy), and aspect ratio (l/d) significantly affect the behavior of the SS-FRP RC column.

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