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Seismic vulnerability assessment of RC bridge piers strengthened with GFRP rebars: a case study

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ABSTRACT: The use of Glass Fiber Reinforced Polymer (GFRP) bars for retrofitting bridges piers under seismic excitation is an advanced technique that offers several benefits due to the material's unique properties, in terms of high strength-to-weight ratio, insensitivity to corrosion, and high durability. Throughout the world, a large number of outdated structures, particularly those made of reinforced concrete, require urgent repairing interventions due to a variety of factors, including environmental effects, inadequate construction details, and neglected maintenance. Engineers who want to increase the longevity and safety of bridge structures in seismic regions can find great benefits in the application of GFRP. An existing bridge is considered as case study. The strengthening design strategy aims to increase the lateral resistance by slightly altering the lateral displacement ductility. To this aim, a hybrid retrofitting with steel and GFRP rebars is designed to be applied through the jacketing technique. The force-deformation curves of the nonlinear plastic hinges are determined using a fiber approach, after validation of the constitutive models. A Pushover Analysis (POA) with lumped plasticity is implemented in order to compare the seismic response of the original structure with the retrofitted one. The capacity of the structure and thus its Seismic Vulnerability Index (SVI) and differences in overall structural response are evaluated.

Keywords: Glass fiber reinforced polymers (GFRP), Hybrid reinforcement, Bridges, Retrofitting, Pushover analysis, Seismic vulnerability.

1 INTRODUCTION

Corrosion of steel reinforcements in concrete structures accelerates their deterioration, reducing the service life of structures and increasing maintenance costs (Devaraj et al., 2023). Glass Fiber Reinforced Polymer (GFRP) bars are a durable alternative, offering corrosion resistance and longevity, thus reducing the need for frequent and costly repairs (Nanni A. et al., 2014; Ruiz Emparanza et al., 2022). However, their inherently fragile nature has limited their deployment, particularly in seismic regions. GFRP reinforced structures exhibit brittle failure characteristics without the formation of plastic hinges, thus offering minimal energy dissipation (Khodadadi et al., 2024). To address this limitation, hybrid reinforcement systems combining steel and GFRP bars present a promising solution. Steel reinforcement provides ductility and energy dissipation, while GFRP enhances durability and corrosion resistance.

Seismic vulnerability assessment of infrastructure plays a pivotal role in ensuring the resilience of civil structures, particularly in seismically active regions. RC bridge piers, as critical components of transportation networks, are especially susceptible to earthquake-induced damage, necessitating effective strengthening techniques. The application of GFRP rebars has emerged as a promising solution due to its high strength-to-weight ratio, corrosion resistance, and ease of application.

The plastic hinge region in a Reinforced Concrete (RC) member is closely related to inelastic rotation and displacement as well as energy dissipation capacity. The physical plastic hinge length of Fiber Reinforced Polymer (FRP) RC columns has been analysed in studies (Li et al., 2025) by measuring the length of the concrete crushing region.

There are few experimental investigations analysing the plastic hinge length (Ibrahim et al., 2018) of hybrid columns with both FRP and steel reinforcement and FRP RC columns with only FRP bars. Therefore, in this study, a direct prediction based on the integration of the curvature distribution was performed to calculate the rotation capacity of the columns.

Nonlinear analysis techniques, particularly pushover analysis, have gained widespread acceptance for seismic assessment. The integration of numerical and experimental approaches, as seen in recent studies on dynamic behaviour analysis, further enhances the reliability of seismic performance evaluations (Tarantini et al., 2023a, 2023b).

This paper aims to contribute to the ongoing research by presenting a case study that evaluates the seismic vulnerability of an RC bridge pier strengthened with GFRP rebars. By employing the N2 method, this study seeks to bridge the gap between theoretical analysis and practical implementation, ultimately contributing to the advancement of seismic risk mitigation strategies in bridge engineering.

2 HYBRID ELEMENTS

2.1 *Moment curvature diagrams*

The moment-curvature diagram (M-χ) for sections with hybrid steel and GFRP reinforcement is constructed by analysing the progressive materials mechanical response by increasing sectional deformation. The concrete-bar deformation compatibility and section congruence equations must be satisfied, ensuring translation and rotation equilibrium (Duy et al., 2024).

In order to simulate the flexural behaviour of a hybrid steel-GFRP RC sections in terms of M-χ diagrams, a fiber method was implemented in OpenSees (S. Mazzoni et al., 2009) The section of the structural element is divided into many elements of finite size, called fibers (Spacone & Filippou, 1991), to which the material behaviour such as unconfined concrete, reinforcing steel, GFRP reinforcement, is assigned by means of the appropriate non-linear constitutive law.

2.2 *Plastic hinges length*

The yielding, plastic and ultimate rotations are used as reference points to build moment-rotation diagrams, which define the non-linear behaviour of the plastic hinges. For RC sections, the yield and ultimate rotations, along with the length of the plastic hinge, are calculated in accordance with (EN 1998-3, 2005). In the case of hybrid steel-GFRP RC sections, the chord rotation corresponding to FRP fracture must also be taken into account. However, there are no established formulations in the literature or in design standards for scenarios where the FRP bars are positioned externally to the steel ones. From the relationship between curvature and rotation (Farouk & Khalil, 2020), it is possible to compute the rotation at steel yielding:

$$\theta_y = \int_0^{h_{pl}} \chi_y(z)\, dz \quad (1)$$

and FRP rupture:

$$\theta_f = \int_0^{h_{pl}} \left[\chi_f(z) - \chi_y(z)\right] dz \quad (2)$$

where: h_{pl} is the beam length over which the bending moment is larger than the yielding moment, $\chi_y(z)$ and $\chi_f(z)$ are the section curvatures distribution along the beam at the FRP rupture and yield levels.

In this research, in order to define the moment-rotation diagram (M-θ), the ultimate rotations (θ_u) corresponding to concrete crushing are defined as proposed for RC sections by (EN 1998-3, 2005), reflecting a very high level of structural displacement during Pushover Analysis (POA).

3 PUSHOVER ANALYSIS

Pushover analysis is a nonlinear static analysis widely used in seismic engineering to assess the performance of structures under earthquake loading. The method involves applying an incremental lateral load pattern to a structural model until a target displacement or collapse mechanism is reached, allowing engineers to evaluate the inelastic behaviour of the structure. Pushover analysis helps in identifying weak points, estimating global and local demand parameters, and assessing potential failure mechanisms (Chopra and Goel, 2002; Fajfar, 2000). The method can be applied to strengthening techniques such as GFRP rebars. By comparing pre- and post-strengthening scenarios, engineers can quantify improvements in seismic resilience.

The primary purpose of pushover analysis is to provide a simplified yet effective approach for evaluating the seismic capacity of structures without resorting to computationally expensive dynamic time-history analyses. It allows for the estimation of key performance parameters such as displacement demand, base shear capacity, and plastic hinge formation, making it an essential tool in performance-based seismic design (FEMA 356, 2000).

The concept of pushover analysis emerged in the late 20th century as a response to the limitations of traditional linear elastic methods in predicting seismic performance. One of the most significant advancements in pushover analysis was the introduction of the N2 method by (Fajfar, 2000), which combined nonlinear static analysis with response spectrum analysis to enhance accuracy. This approach has been widely adopted due to its balance between simplicity and effectiveness.

Pushover analysis offers several advantages over alternative seismic assessment methods, particularly in terms of computational efficiency and ease of implementation. Unlike nonlinear time-history analysis, which requires significant computational resources and detailed ground motion records, pushover analysis provides a more practical approach for engineers to assess structural performance under seismic loads (Chopra and Goel, 2002).

The main advantages of pushover analysis include fewer computational resources compared to nonlinear dynamic analysis, identification of weaknesses, and application in retrofitting design. However, pushover analysis also has inherent limitations such as load pattern dependency (Antoniou and Pinho, 2004), limited representation of dynamic effects (it does not fully capture the dynamic characteristics of seismic excitation, such as frequency content and duration effects (Fajfar, 2000)), challenges in modelling complex structures.

In this study, specific details regarding the application of pushover analysis, the N2 method, and the evaluation of the Seismic Vulnerability Index (SVI) will be discussed within the context of RC bridge piers strengthened with GFRP rebars. This case study will illustrate how these methods are integrated to provide a comprehensive assessment of seismic vulnerability.

4 CASE STUDY

4.1 *Geometry and material properties*

The bridge under study is a RC structure consisting of multiple spans supported by RC piers as shown in Figure 1 (a). The piers are designed to sustain both vertical loads from the superstructure and lateral loads induced by vehicles and seismic forces. The typical pier is a 3D frame, with a height variable between 8.50 and 52.00 m. The bridge deck is composed of 4 simply supported beams with a span of 20 and 30 m, while the foundation consists of both direct and deep foundations.

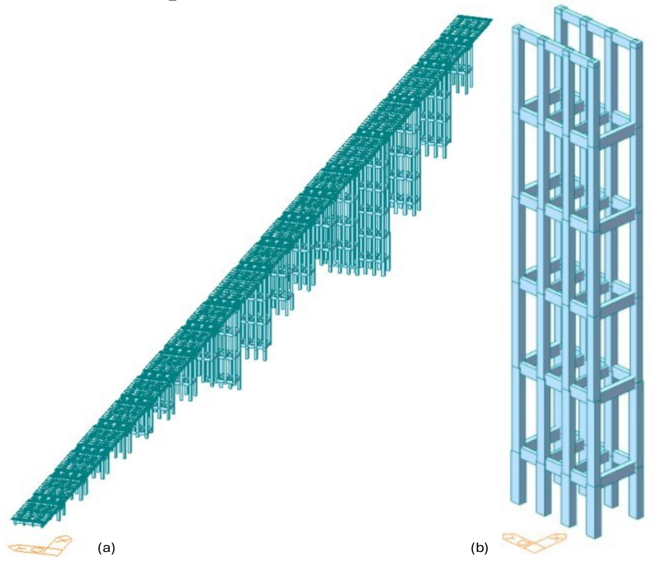

Figure 1. FE model of the considered case study: (a) entire bridge and (b) isolated single 3D-frame pier analysed.

The design material properties for the bridge piers are as follows:

- concrete: compressive strength (f_{cd}) 35.1 MPa for As-built and 31.7 MPa for the jacketing;
- steel bars: yield strength (f_{yd}) 35.1 MPa for As-built and 533.4 MPa for the jacketing;
- GFRP bars: tensile strength (f_{fd}) 437.8 MPa, modulus of elasticity (E_f) 60 GPa.

The structural elements analysed in pure-bending and axial-bending regime in this study are characterised by an existing section in ordinary reinforced concrete and an external RC jacketing with longitudinal GFRP bars.

Figure 2 shows an example of the geometry of the original cross-section of the external transverse crossbeam and the increased cross-section after concrete jacketing with steel bars.

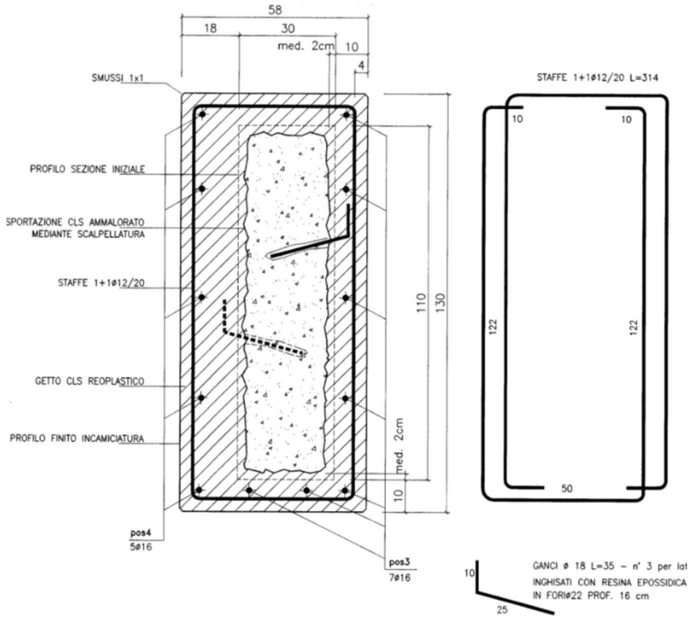

Figure 2. Geometry of the steel RC jacketing of external transverse crossbeam.

To carry out the POA, therefore, starting from the moment-curvature diagrams, the moment-rotation response of plastic hinges are derived. Currently, specific design standards for hybrid-RC elements are not yet provided. For this reason, the material design properties were calculated according to EN 1992-1-1 (2005) for concrete and steel and according to ASTM D8505/D8505M-23 (2023) and CNR-DT 203/2006 (2006) for GFRP bars. The retrofitted hybrid FRP-steel RC columns and beams, in relation to the different reinforcement ratios of FRP and steel, have a flexural failure mode I (Zhou et al., 2021): FRP reinforcement rupture after tensile steel reinforcement yielding with concrete crushing (lightly reinforced elements). The M-χ diagrams were obtained by means of the fiber model validated by analytical calculation. Figure 3 compares the M-χ diagrams of the As-built, steel strengthened and GFRP strengthened external transverse crossbeam.

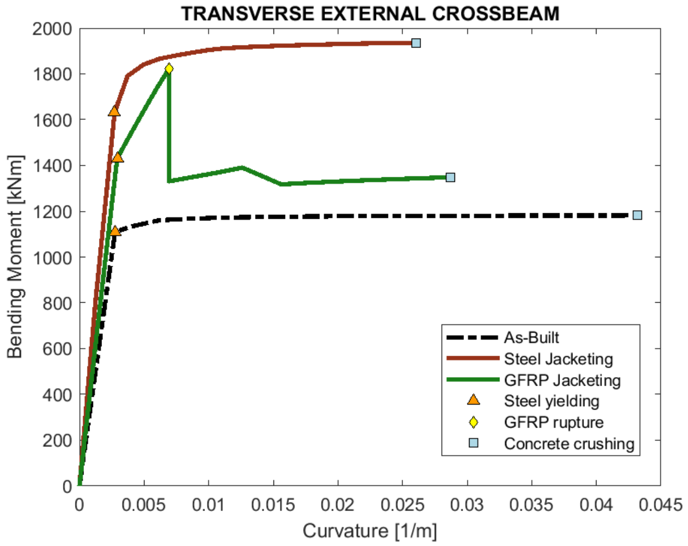

Figure 3. Moment-curvature diagrams for As-built, steel and GFRP RC jacketing.

4.2 *Development of the Finite Element Model*

A Finite Element (FE) model of the bridge pier was developed using Midas GEN software (Fig. 1b). The structure was modelled as a pier with a fixed base with the related masses and incorporated M-θ plastic hinges based on lumped plasticity (Givonetti et al., 2023).

4.3 *Implementation of POA and N2 Method*

The pushover analysis was conducted by incrementally increasing lateral loads until the structure reached its ultimate displacement capacity. Two different load profiles were used: uniform and modal.

The N2 method was then applied. It follows these steps:

- Pushover Analysis: A nonlinear static analysis is conducted to derive the structure's capacity curves related to multiple load profiles (Fig. 4).
- Transformation to an SDOF System: The MDOF systems are reduced to equivalent SDOF representations using modal participation factors.
- Transformation to an equivalent SDOF System bilinear curve: The SDOF systems capacity curves are converted to equivalent SDOF bilinear curves.
- Demand-Capacity Comparison: The capacity curve is converted into spectral coordinates and intersected with the demand spectrum.
- Performance Point Identification: The intersection determines the expected displacement demand and structural performance level.

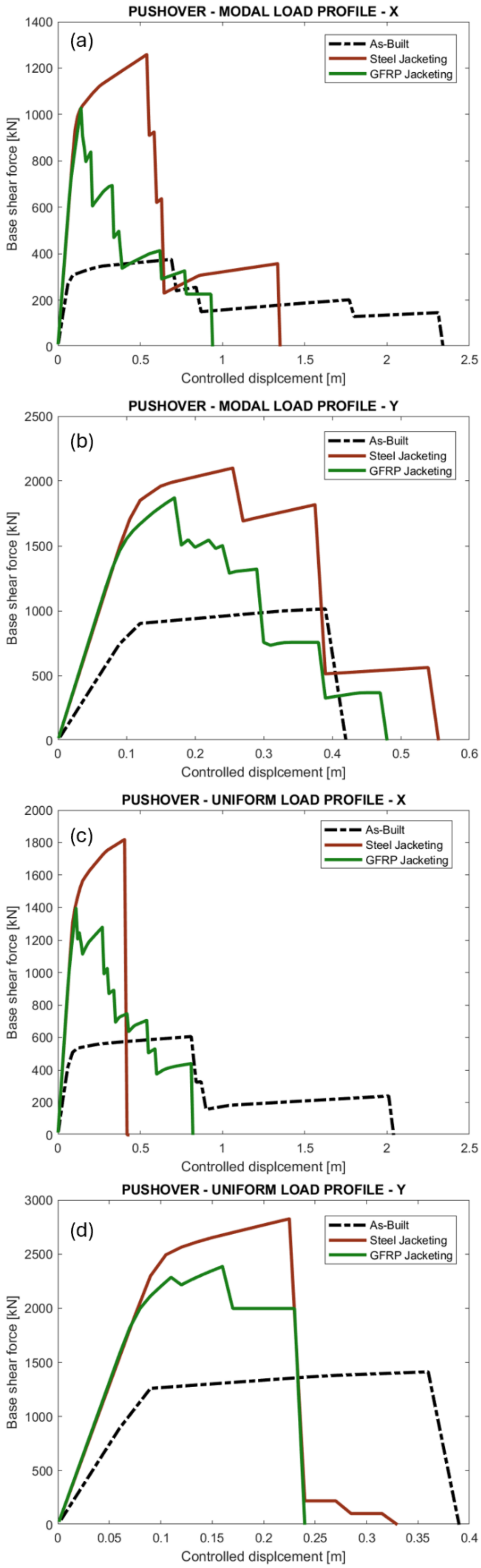

Figure 4. Pushover curves MDOF for As-built, steel and GFRP RC jacketing: modal load profile in X (a) and Y direction (b), and uniform load profile in X (c) and Y direction (d).

At the end of the process, the Seismic Vulnerability Index (SVI) is evaluated as the ratio between the Peak Ground Acceleration (PGA) capacity and PGA demand. This index provides a quantitative measure of the safety margin of a structure under seismic loading conditions (Tarantini et al., 2023a, 2023b):

$$\zeta_E = \frac{PGA_c}{PGA_d} \quad (3)$$

The SVI of the three structural systems (As-built (AB), steel RC jacketing (SCJ), and GFRP RC jacketing (GCJ)) are reported in Table 1. The PGA_d for the specific site is equal to 0.079 g.

Table 1. Peak Ground Acceleration capacity (PGA_c) and Seismic Vulnerability Index (ζ_E).

		X direction		Y direction	
		Uniform load profile	Modal load profile	Uniform load profile	Modal load profile
AB	PGA_c [g]	0.082	0.051	0.189	0.135
	ζ_E	1.040	0.642	2.389	1.709
SCJ	PGA_c [g]	0.153	0.110	0.248	0.182
	ζ_E	1.937	1.393	3.138	2.300
GCJ	PGA_c [g]	0.117	0.085	0.222	0.163
	ζ_E	1.477	1.073	2.805	2.066

5 RESULTS AND DISCUSSION

The MDOF capacity curves presented in Figure 3 (a) provides a clear comparison of the seismic performance of the bridge pier in its as-built configuration and after two different strengthening techniques: steel RC jacketing and GFRP RC jacketing. The pushover curves illustrate the seismic response of the bridge pier under a modal load profile applied in the X direction.

The base shear force is plotted against the controlled displacement, allowing an assessment of the stiffness, maximum base shear, and ductility of each system.

The as-built structure (black dashed line) exhibits the lowest initial stiffness and strength, reaching a peak base shear of around 400 kN before experiencing significant softening. The steel RC jacketed system (brown line) displays a substantial increase in initial stiffness and strength, achieving a maximum base shear of approximately 1250 kN, indicating a considerable enhancement in load-carrying capacity. The GFRP RC jacketed system (green line) also demonstrates an increase in strength but with a slightly different post-peak behaviour compared to RC jacketing alone.

The seismic vulnerability indexes shown in Table 1 show that both retrofitting interventions ensure that the structure is safe against seismic actions.

It is useful to note that, for the same geometric dimensions and mechanical percentage of reinforcement, the steel RC jacketing intervention achieves a higher SVI than the GFRP RC jacketing.

6 CONCLUSIONS

The methodology presented in this paper provides a systematic approach for evaluating the seismic vulnerability of RC bridge piers and quantifying the benefits of GFRP strengthening. By combining pushover analysis with the N2 method and expressing results through the Seismic Vulnerability Index. The use of hybrid concrete jacketing with steel and GFRP bars successfully increased strength but not the ductility of RC bridge piers. The use of GFRP bars, on the other hand, increases the durability of the infrastructure.

The N2 method effectively assessed the seismic performance of the reinforced structure. The hybrid jacketing in terms of SVI positively fulfils the seismic requirements (ζ_E=1.073) even though it is 22% less than the equivalent steel jacketing (ζ_E=1.393).

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