Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.81

SEISMIC BEHAVIOUR OF BEAM-COLUMN JOINT IN R/C FRAMES AND STRENGTHENING WITH FRP

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Abstract

Multi-story reinforced concrete structures in previous periods, in general, do not meet current seismic design code requirements, including the poor materials and execution of civil engineering works. In the scope of this, is analyzed the behavior of the structures during the Earthquake of November 2019, in Albania, specifically in different building stocks.

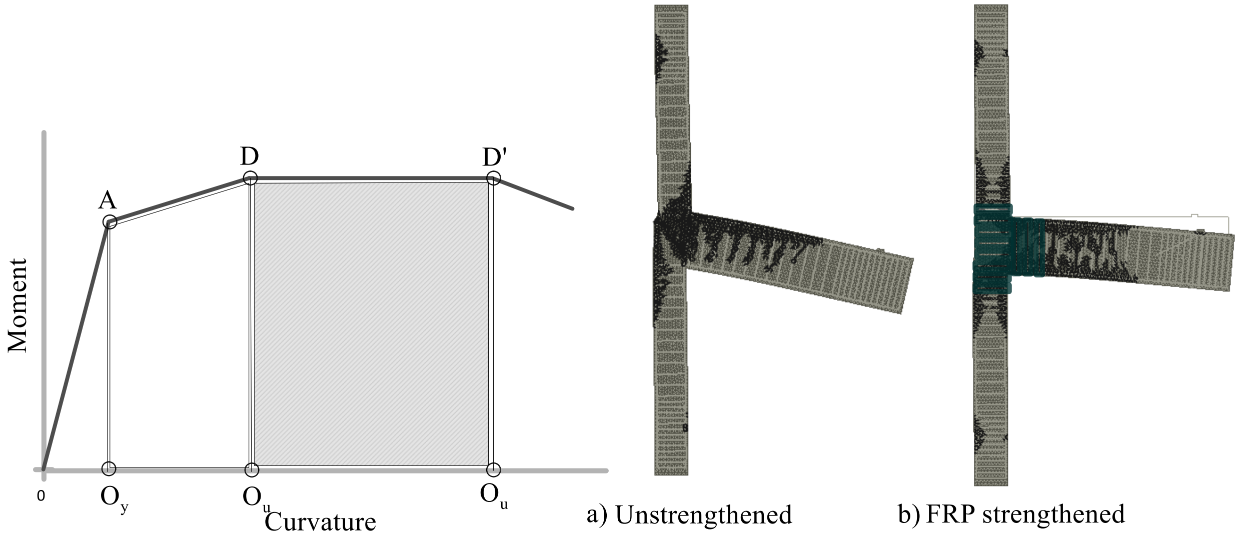
Typical structural deficiencies observed in reinforced concrete (R/C) frame buildings affected by the 2019 earthquake reveal that many collapses occurred could be attributed to the poor quality of construction and use of non-ductile detailing and during the assessment that deficiency beam–column joints can jeopardize the integrity of structures. In general, it is accepted that beam-column joints are critical elements of reinforced concrete buildings subjected to lateral loads and that they may require specific design. Assessment reports have often indicated that beam-column joints, which are one of the most vulnerable and critical structural elements, often suffer shear and/or bond (anchorage) failures leading to a partial or total collapse of the structure.

This paper will present some of the destructive and non-destructive tests specifically to the beam-column joints and techniques using fiber-reinforced polymers (FRP) for strengthening. Strengthening of beam-column joints by FRP materials nowadays is treated with various analytical approaches integrated in different software. Various analyses have been conducted and a practical proposal for retrofitting is presented in cohesion with the study case and the implementation.

Keywords: beam-column joint, moment-resisting frame, seismic behavior, strengthening, FEM analysis

1 Introduction

An earthquake generates multiple seismic loads of varying intensities that can damage a building, necessitating the design of all components to withstand such loads. The reinforced concrete (R/C) frame joints are crucial in providing a continuous load path to transfer applied loads between beams and columns. These joints experience significant forces during an earthquake and can reach their maximum capacity before the building stops swaying. Inadequate design and detailing of the joints can lead to premature failure, causing the structure to collapse. Therefore, proper detailing and design of R/C frame joints are critical for ensuring the building's stability and safety during seismic events[1]. At the beam-column joint, transversal reinforcement is used to enhance the ductility of the element and, therefore, the structure. The amount of seismic energy absorbed by joints depends on how much the column and beam deform without reaching their ultimate capacity[2]. Fig. 1 illustrates the behavior of an element under bending, from the initial cracks to ultimate deformations. Under both permanent and transient design situations, the structure is calculated with linear-elastic approaches and has linear elastic behavior. However, under seismic loads, the elements enter the plastic phase of non-elastic behavior. As shown in Figure 1, the plastic zone is from point A to point D. Point D' is reached through retrofitting. The figure also demonstrates how the use of additional exterior reinforcement with FRP extends the plastic zone. This kind of improvement provides a significant increase in the strength of the joint, which is essential for horizontal loads. The purpose of this paper is to investigate the feasibility of retrofitting the joints in RC frames, specifically in older buildings[3]. The case studies used in this research were chosen to represent the in-situ conditions of collapsed buildings in Albania. Whether it's inadequate material quality or reinforcement ratio, the examples show the clear difference in behavior between an unreinforced joint and one reinforced with FRP.



a) Unstrengthened b) FRP strengthened

Fig. 1. Beam/column plastic zone enhancement.

2 Joints in resisting frames structures

Reinforced concrete is a popular construction material due to its strength, durability, and low maintenance cost. However, concrete beams and columns without reinforcing bars lack ductility and are brittle. Although steel reinforcement adds ductility to the structure, it alone does not guarantee the desired behaviour of the beam-column joint. Comprehensive and adequate joint detailing is critical to ensure its performance and ability to withstand anticipated loads. Building codes prescribe detailed requirements for joint detailing, including member sizes, reinforcement ratios, anchorage lengths, and flexural strength. Compliance with these codes ensures the desired performance of the structure under various loading conditions, ensuring safety and structural integrity[4]. A nonlinear analysis is necessary to understand the behaviour of a reinforced concrete (R/C) frame during seismic events. The collapse of an R/C frame is due to the formation of a plastic hinge mechanism caused by the cycling load on frame components that develops a hysteric loop in the beam/column. During high seismic forces, failure occurs in the joint due to the failure of the diagonal compression strut and the development of large shear cracks, resulting in spalling of the concrete core, buckling of rebars, beam failure, and, ultimately, column failure.

Tests have been conducted to investigate the effects of different joint configurations on the seismic performance of R/C frames. Results suggest that joint performance improves when the hooks' ends are bent into the joint core. Additionally, 14 experiments examined the impact of axial column force and reinforcement on joint behaviour. These experiments provide valuable insights into the behaviour of R/C frames under seismic loading, which can inform the development of more robust and reliable structures[5]. It is noticeable that specimens with higher axial load had delayed shear cracking. Shear reinforcement within the joint gave higher capacities and gradual strength degradation. Depending on the joint's reinforcement detailing, damage mechanisms are also different. As for the system, early cracks in joints reduce the rigidity of the system and cause an uncontrolled redistribution of the stresses. Some of those cracks are shown in the figures below[6].

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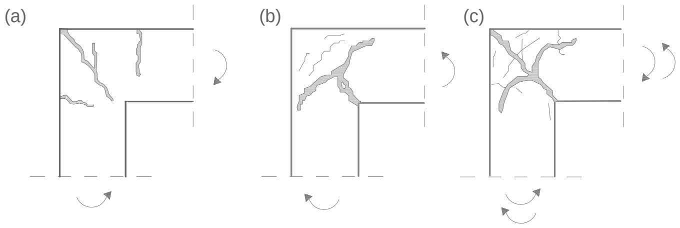

Fig. 2. (a) Compression of the inner fibers; (b) tension of the inner fibers and; (c) alternative moment.

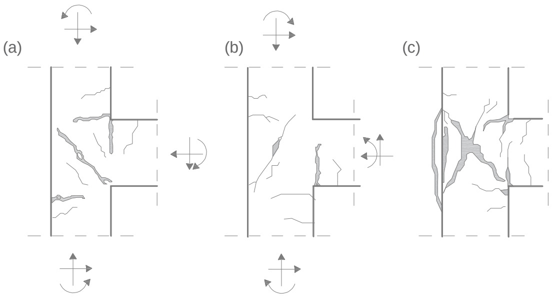

Fig. 3.(a) Compression of the lower fibers; (b) tension of the lower fibers and; (c) alternative moment.

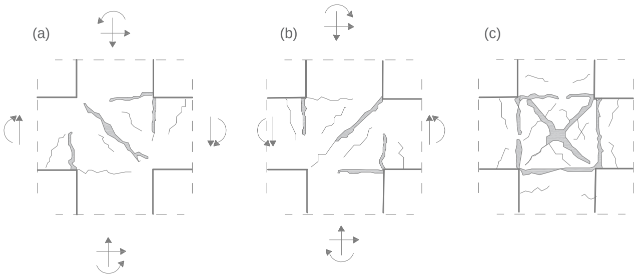

Fig. 4. Interior joint: (a)Horizontal load from the right side; (b) Horizontal load from the left side and (c) alternative horizontal load.

3 Assessments in Albania

The recent earthquake in Albania highlights the critical significance of proper detailing, dimensioning, appropriate construction materials, and foundation design. The failure of many buildings during the earthquake was attributed to the removal of masonry walls on the first floor, creating soft stories and discontinuity in the rigidity of the structural system, resulting in the structure's collapse at the early stages the earthquake. Various factors, such as concrete quality discontinuity, low concrete strength, construction errors, artistry, and steel bar corrosion, can adversely impact the lateral stiffness of the structural system[7]. The in-situ testing proves the latter statement. The quality of concrete was assessed using both non-destructive and destructive methods which are shown below[8]. For a more detailed analysis, we used in-situ testing methods for evaluating concrete strength with Hammer Schmidt and the damaged parts

to evaluate the concrete by taking and preparing samples with dimensions 60x60x60mm for laboratory investigations as described in Table 1.

Table 1. – Test results – Nondestructive (Non damaged part) and Destructive (Damaged part) [8]

Pos	X_{min}	X_{avg}	f_{cki} (N/mm^2)
Circular	30	37.6	38.8

Column			
Rectangular Column	33	38.3	40.0
Rectangular Column (laboratory test)	N/A	N/A	8.58

Fig. 5. Plastic hinge at the columns of multi stories building, inadequate materials and other deficiencies.

3.1 Retrofitting strategy

FRP exhibits elastic behaviour, characterized by the absence of a distinct yield plateau. Its tensile strength significantly exceeds that of steel, making it an ideal choice for external reinforcement layers, which enhance joint resistance. The present study involves column jacketing and single-sided joint cover retrofitting, utilizing the Mapewrap system fabrics. The approach adopted for quantifying the contribution of FRP reinforcement is based on the guidelines outlined in the recent FIB Bulletin 90, which addresses the use of FRP for reinforcing existing structures[9]. A two-dimensional sectional analysis program for beams and columns is used to calculate the strength and ductility of a R/C cross-section subjected to shear, moment, and axial load, thus extracting the moment-curvature and moment-max cracks joint curves[10]. The calculations are based on the following approaches: Shear tensile stress of FRP (expression (2)); shear tensile stress in the joint (expression (3)) and shear tensile capacity of the joint (expression (4)).

$$V_{jh.d.max} = V_{jh.d} = \frac{M_{Ed.sx}}{0.9(h_{b.sx} - c)} + \frac{M_{Ed.dx}}{0.9(h_{b.dx} - c)} - V_{Ed} \qquad (1)$$

$M_{ed,sx}$ – Bending moment on the left beam
$M_{ed,dx}$ – Bending moment on the right beam
c – Cleare concrete cover
$h_{b.dx}$ – Height of the right beam
$h_{b.sx}$ – Height of the left beam
V_{Ed} – Shear force acting on the base of the upper column

$$\sigma_{jt,FRP} = \varepsilon_{f.d}\, E_f\, A_f / \left(\frac{b_c\, h_c}{sin\theta}\right) \qquad (2)$$

$$\sigma_{jt} = \left| N/2A_j - \sqrt{\left(N/2A_j\right)^2 + \left(V_j/A_j\right)^2} \right| \leq 0.3\,\sqrt{f_c} \qquad (3)$$

In accordance with what is prescribed in the guideline, the resistant capacity of the node panel is fixed at the drawing of a main traction stress equal to 0.3√fc. The question comes calculated as a function of the knot shear, Vj, and the normal force acting at the base of the primary column.

$$\sigma_{jt} \le 0.3\sqrt{f_c} + \sigma_{jt,FRP} \qquad (4)$$

4 Study case

A representative model is developed referencing common structures in Albania, and the internal forces taken into consideration here are from the joints of the first floor. The following examples are presented here; 3D geometry of study case where interstory height is 2.7m; bay dimensions are 4mx4m, the number of stories is 6 and referent modes are T_1=0.95s; T_2=0.93s; T_3=0.77s. The observed damage to buildings caused by earthquakes is various, and for analysis, three main study cases have been considered: study case 1- Inadequate detailing, good material properties, study case 2- Inadequate material properties, moderate detailing and study case 3- Moderate detailing and material qualities.

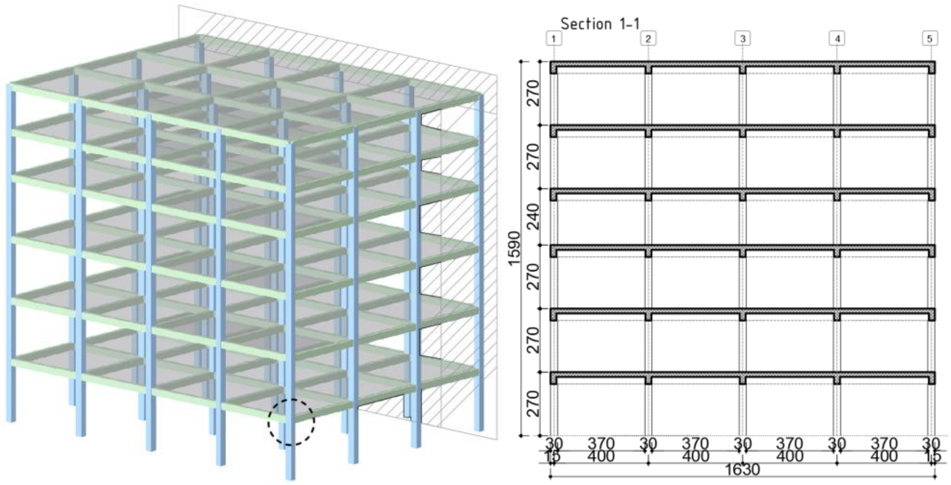

Fig. 6. 3D geometry of the reference structure and referent plane section.

ATENA in combination with GiD is used to conduct FEM analysis because it provides the possibility to model the strengthening of different structures[11]. ATENA-GiD is a finite element-based software system specifically developed for the nonlinear analysis of reinforced concrete structures. The reference experimental investigation uses light FRP strengthening solutions that are applied to the joint panel completely from the exterior of a building[12]. The investigated FRP-strengthening layouts are designed according to minimize the level of disruption caused by their application. Material model for 1D reinforcement is the most suitable for FRP lamellas where lamellas are more line strengthening elements than planar, they are modelled as 1D reinforcement elements[13].

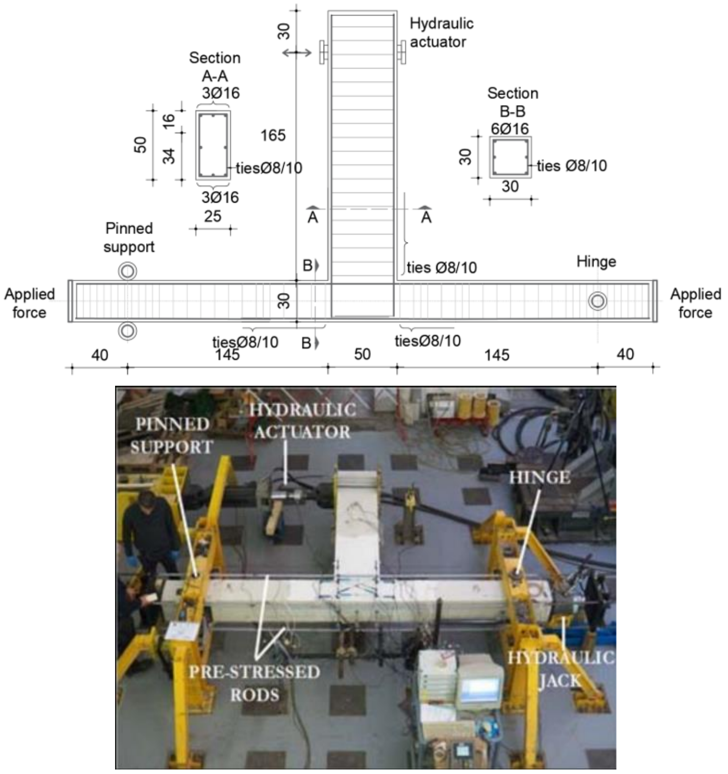

Fig. 7. (a)Description of geometry and reinforcement; (b) Instrumentation and test setup.

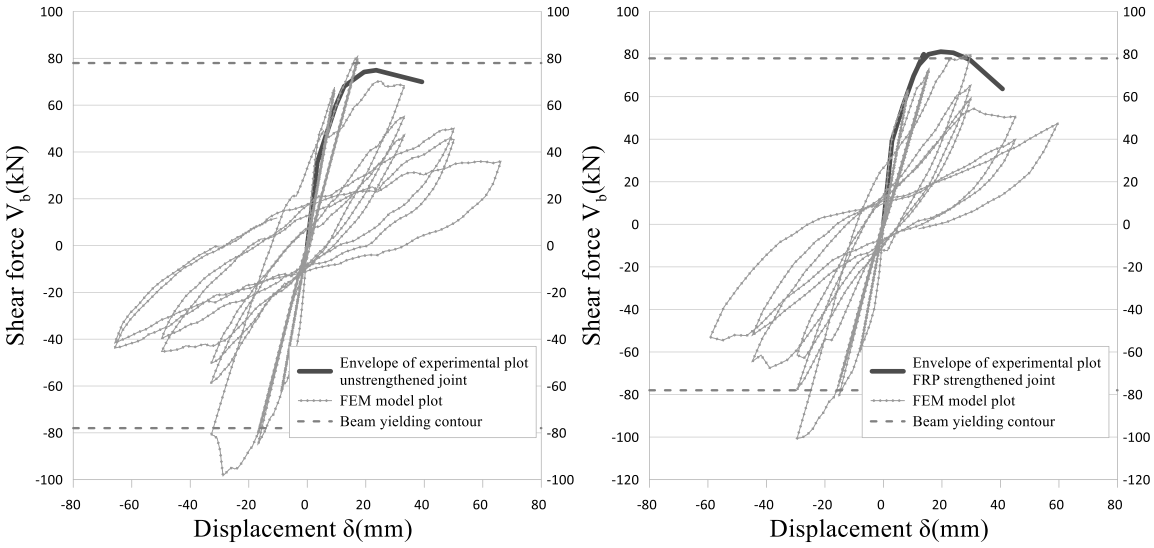

Fig. 8. Shear-drift response of tested joints: (a) envelope of unstrengthened joint vs FEM model plot; (b) first cycle envelope of FRP strengthened joint vs FEM model.

FE analysis of joints under cyclic incremental loading is conducted in reference to the control joint. Material constitutive laws and bond slip parameters of FRP are determined through an iterative process. Iteratively the procedure for obtaining a new bond slip function of FRP is progressively repeated until an acceptable adjustment of the load-displacement diagram is achieved where the percentage of error is achieved.

4.1 Study Case 1

The primary factors that characterize Study Case 1 are inadequate detailing and material properties, as indicated by the data presented in table 4. The moment-curvature diagram, which illustrates the capacity of the column and beam, further supports this assessment. Additionally, data pertaining to the FRP strengthening system, as presented in [14], further highlights the deficiencies in the structural system. These examples demonstrate the significance of proper detailing and quality material properties in ensuring the structural integrity of a building.

Table 2. Geometry of the joint for all study cases

	Top col.	Bottom col.		Left beam	Right beam
h_c [mm]	300	300	h_b [mm]	500	0
h_c [mm]	300	300	h_b [mm]	250	0
				Left	Right
Bay length [mm]				4000	0
				Top	Bottom
Interstory height				2700	2700

Table 3. FRP “MapeWrap C BI-AX 300 - E 256” mechanical properties for all study cases

σ_k	ε_{fk}	E_f	t_f	Fibers	f_{fd}
4830 MPa	0.021%	230000MPa	0.164mm	Carbon	3421.25MPa

Table 4. Column beam detailing data for study case 1

Concrete	D_{max}	$C_{o.nom}$	Rebars f_y
C20/25	31.5mm	2.0cm	240MPa

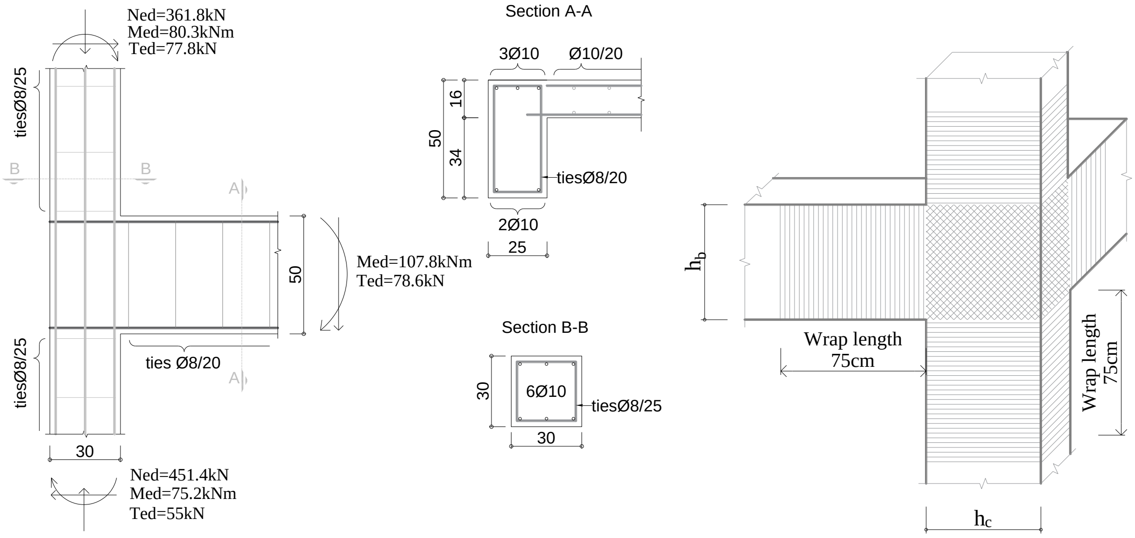

Fig. 7. Reinforcement detailing of the joint and the layout of the strengthening scheme.

The U-wrap end anchorages typically involve the utilization of uniaxial fabric that is extended by approximately 750 millimeters at the terminus of the beams and columns that frame the joint.

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The moment-curvature diagram depicts the correlation between the bending moment (M) and curvature (Φ) of the beam/column, with a characteristic shape observed in all study cases. This diagram serves as a tool to evaluate the stiffness of the beam/column, its ultimate strength, load-deflection behaviour, and design considerations. The vertical axis represents the bending moment, while the horizontal axis indicates the curvature (mrad/m). Additionally, the moment-max crack width diagram represents the element's behaviour, where the inertia moment, stiffness, and other parameters decrease as the crack width increases.

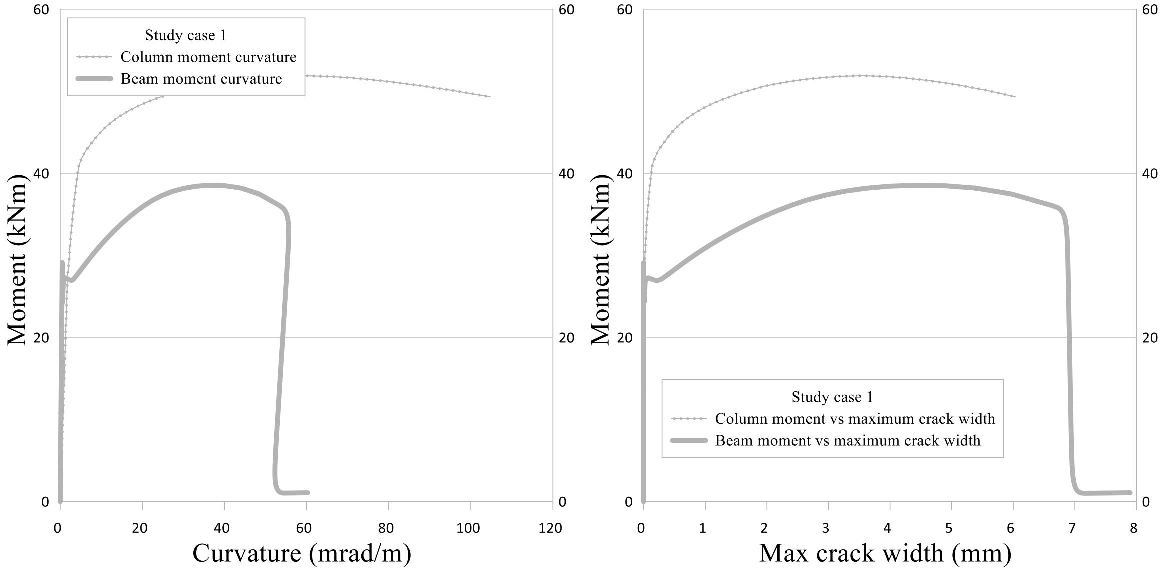

Fig. 8. (a)Beam and column moment-curvature diagram; and (b)Moment-max crack width diagram.

In the first study case, the column moment yield point exceeds the maximum moment resistance of the beam, meeting the criteria for satisfaction as per the Eurocode 8 standards. A comparison of the diagrams from all study cases allows us to infer that favorable material properties significantly impact the behaviour of the beam/column system. At the same time, the reinforcing measures exert a more significant influence on the joint's response.

4.2 Study Case 2

The analysis of Study Case 2 reveals moderate detailing and inadequate material properties, as evidenced by the data presented in 5. Moderate detailing and inadequate material properties of R/C joints can reduce the capacity to resist lateral forces from earthquakes, resulting in premature failure. Inadequate material properties can lower strength and ductility, while moderate detailing can result in insufficient reinforcement and anchorage. These factors increase the risk of joint failure, causing significant damage to the structure and jeopardizing the safety of occupants. Properly detailing and using high-quality materials are essential for optimal joint performance during seismic events.

Table 5. Column beam detailing data.

Concrete	**D_{max}**	**$C_{o.nom}$**	**Rebars f_y**
C12/15	31.5mm	2.0cm	400MPa

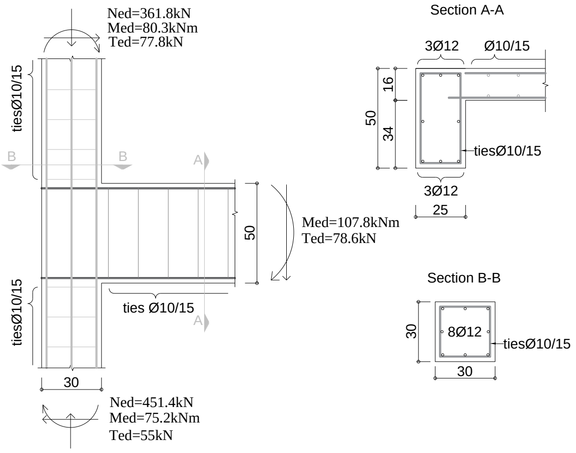

Fig.9. Reinforcement detailing of the joint.

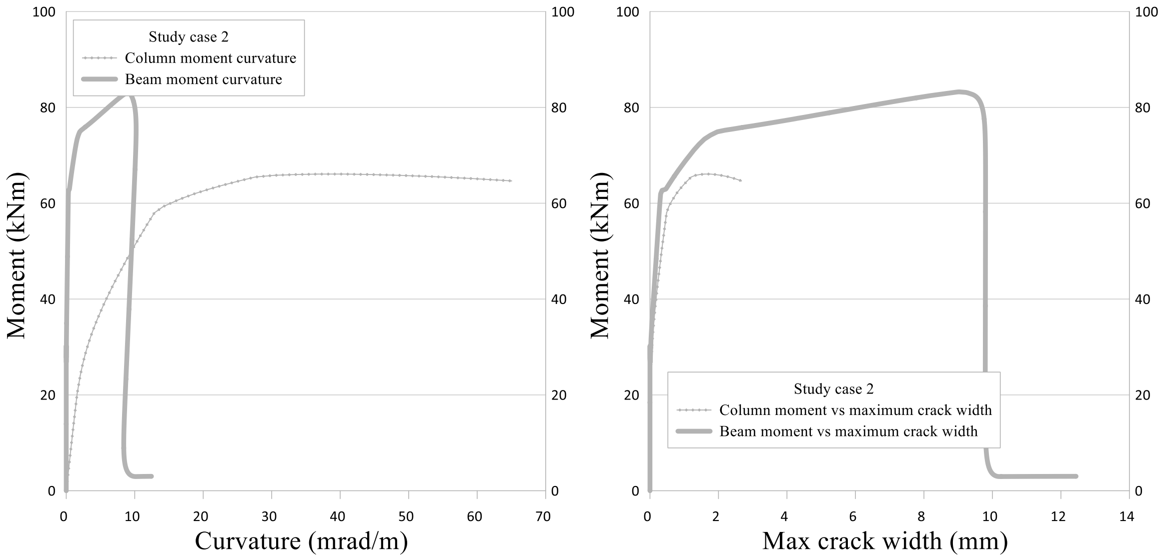

Fig. 10. (a)Beam and column moment-curvature diagram; and (b)Moment-max crack width diagram.

The diagram above demonstrates that the column moment yield point is significantly lower than the maximum moment resistance of the beam. Despite the joint possessing moderate detailing, its response is unsatisfactory.

4.3 Study case 3

The examination of Study Case 3 elucidates a state of moderate detailing and material characteristics substantiated by the data presented in Tables 12 and 13. The moment-curvature and moment crack width diagrams, derived from the aforementioned tables, provide additional evidence to support this classification. This instance exemplifies the interdependence between the quality of detailing and material attributes in determining the structural soundness of a building.

Table 5. Column beam detailing data

Concrete	**D$_{max}$**	**C$_{o.nom}$**	**Rebars f$_y$**
C20/25	31.5mm	2.0cm	400MPa

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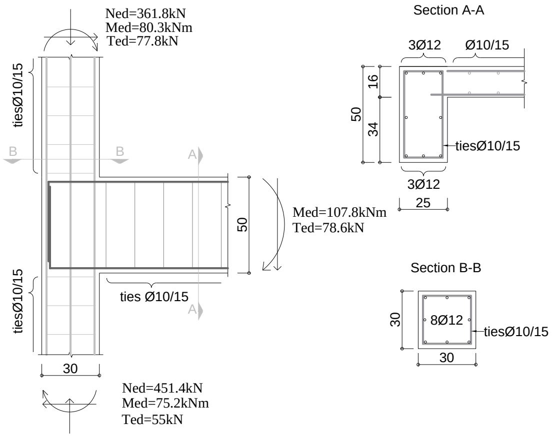

Fig. 11. Reinforcement detailing of the joint

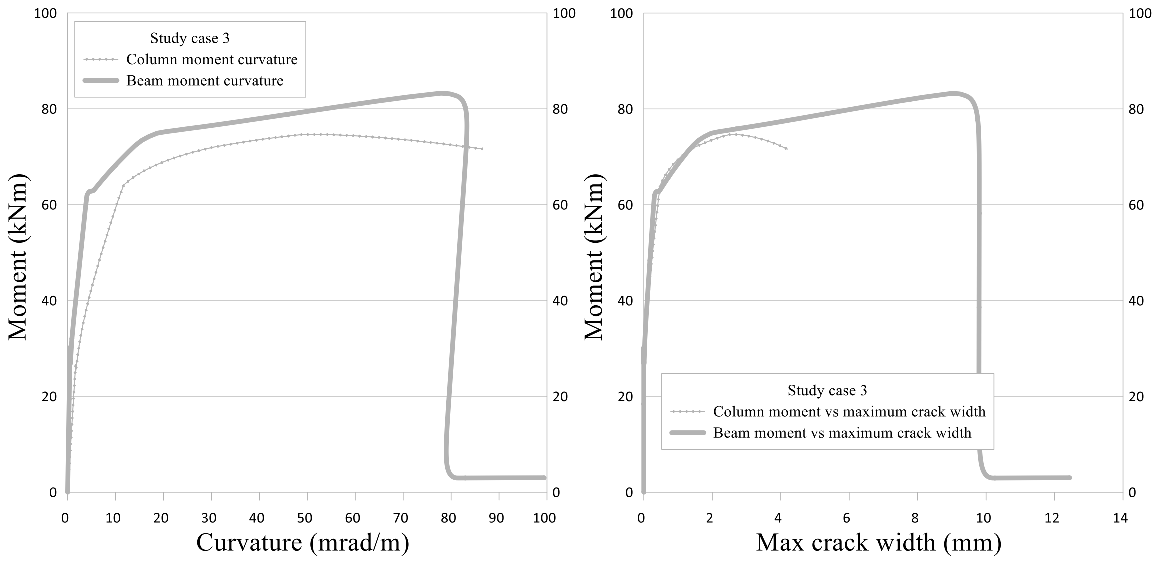

Fig. 12. (a)Beam and column moment-curvature diagram; and (b)Moment-max crack width diagram

In the above diagrame the beam and column have a similar response to the load applied. All three study cases give the capacity of the joint, which, when compared is below the demand.

Table 6 Results of joint capacity and demand values for all study cases.

		Study case 1	**Study case 2**	**Study case 3**
Capacity	$0.3\sqrt{f_{cd}}$	0.4	0.34	0.4
Demand	σ_{jt}	1.05	1.05	1.05
Result	$0.3\sqrt{f_{cd}} \geq \sigma_{jt}$	Failure	Failure	Failure

Table 7 Joint safety check after strenghtening. The following results have those inputdata on n_s=1; n_s=1; n_l=1; η_a=0.85; Υ_f=1.1 and the data in **Error! Reference source not found.**

		Study case 1	**Study case 2**	**Study case 3**
Capacity	$0.3\sqrt{f_{cd}} + \sigma_{jt.FRP}$	1.26	1.09	1.26
Rezult	$0.3\sqrt{f_{cd}} + \sigma_{jt.FRP} \geq \sigma_{jt}$	Satisfied	Satisfied	Satisfied

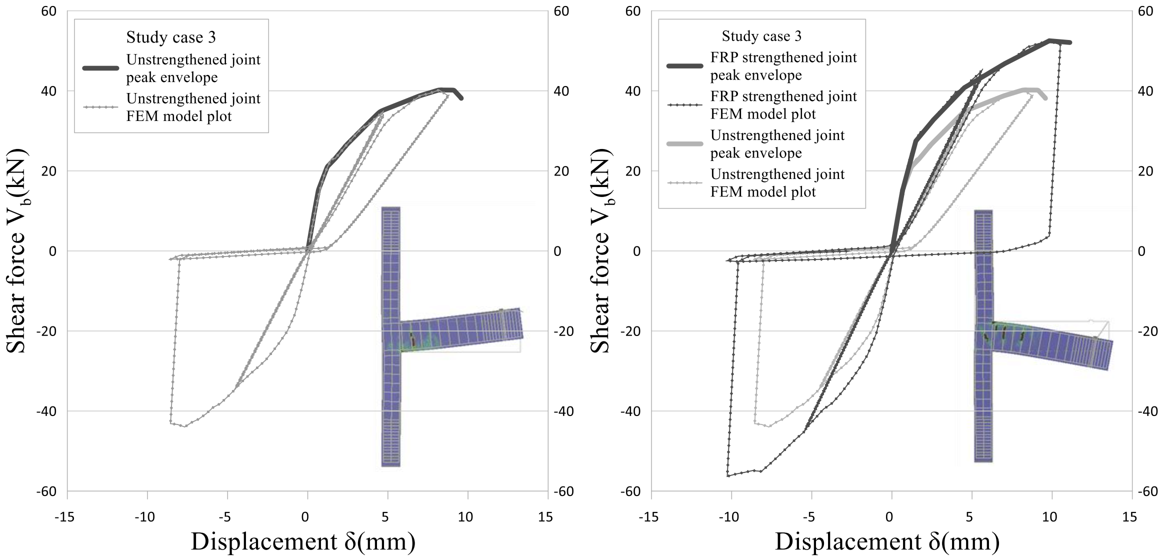

Fig. 13. Joint shear-drift response of analyzed joints: (a) FEM model plot and peak to peak envelope of unstrengthened joint; and (b) FRP strengthened vs unstrengthened joint

5 Conclusions

In seismic design scenarios, the behaviour of reinforced concrete (R/C) frame joints plays a pivotal role in determining the failure mechanism of the structure. Typically, the tensile shear capacity dominates the failure mode, while the compression strut exhibits adequate capacity.

The use of FRP as a strengthening material in exterior or corner joints can increase the shear tensile capacity. Notably, up to three layers of FRP can result in a substantial improvement in capacity, beyond which further layering is not recommended due to diminished retrofitting efficacy.

The layout scheme should incorporate mechanical anchors to prevent FRP failure resulting from low bond strength between FRP and concrete. Examples of such anchors include a U-wrap at the end of the beams or FRP spike anchors.Under seismic design situations the deformation of R/C frame joints determine the collapsing mechanism of the structure.

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