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Experimental assessment of the flexural/shear strengthening effectiveness of new CFRP bars

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Abstract

The potential of a new carbon fibre reinforced polymer (CFRP) bar (CutInov) is explored for the simultaneous flexural and shear strengthening of reinforced concrete (RC) beams. This bar has a stick geometric configuration, with one part applied according to the near surface mounted (NSM) technique and the other according to the embedded through section (ETS) technique, both connected with a smooth transition zone. The NSM part aims to increase the flexural capacity of the RC element, whereas the ETS part, inclined at 45° relative to the RC beam's axis, aims to provide shear strengthening and to avoid premature end debonding and rip-off failure modes to the NSM part. To avoid premature rupture at the transition zone of this bar, CFRP fan-type anchors are applied in the critical regions of the beam. An experimental programme with almost real-scale RC beams was executed, composed of a reference beam (Ref) and two beams strengthened with CutInov bars, one with (3CI_A) and the other without CFRP anchors (3CI). Compared to the Ref beam, the 3CI beam presented an increase of 55%, 71%, and 79% in terms of load at a deflection corresponding to serviceability limit state conditions, load at yield initiation of the flexural steel reinforcement, and maximum load, while 3CI_A have even developed better indicators, 61%, 95%, and 117%, demonstrating the efficiency of the CFRP anchors.

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Keywords: RC beams; Flexural and shear strengthening; New CFRP bar; CFRP anchor; Experimental tests

1. Introduction

Carbon fibre reinforced polymer (CFRP) systems have been used with notable effectiveness on the flexural, shear and punching strengthening of reinforced concrete (RC) structures using external applied reinforcement (EAR) and Near Surface Mounted (NSM) techniques (Bakis et al. 2002, Billota et al. 2015, Faria et al. 2014, ACI PRC-440.2-23, *fib* bulletin 90). However, the level of flexural strengthening effectiveness when using EAR and NSM decreases with the quality of the concrete substrate, stiffness and flexural strengthening ratio ($\rho_f = A_f /(b\ d_f)$, where A_f and d_f are the cross-section area and internal arm of the CFRP, and b is the width of the element's cross section) of CFRP due to premature debonding of CFRP and/or concrete rip-off (Rezazadeh et al. 2015). In shear strengthening with EAR, premature debonding is also a current failure mode, mainly when CFRP is applied in the lateral faces of the RC beam or in a U configuration (Mostofinejad et al. 2016). The shear strengthening effectiveness also depends on the quality of the concrete substrate, the stiffness and shear strengthening ratio, the inclination of the EAR-CFRP arrangements, the depth and type of the element's cross-section (rectangular vs T), and the flexural and shear reinforcement ratios (Mohammadi et al. 2023). The major part of these variables also affect the NSM shear strengthening effectiveness, but since the CFRP laminates are inserted into grooves executed on the concrete cover of the RC beams, the shear strengthening effectiveness this technique provides per volume of applied CFRP is higher than that guaranteed by EAR (Barros et al. 2007). However, both EAR and NSM techniques are not applicable to RC elements with concrete substrate quality classified as non-structural concrete, whose damage level is generally assessed by pull-off tests. This level of damage can be caused by fire events, corrosion of existing steel reinforcements, etc. For the shear strengthening of this type of elements, Embedment Through Section (ETS) is very efficient (Valerio et al. 2009).

A new CFRP reinforcement was proposed to combine the flexural strengthening effectiveness of CFRP applied according to the NSM technique with the shear strengthening effectiveness applied following the ETS technique. This CFRP, designated by CutInov, has a sticker configuration, with two parts, one mainly dedicated to flexural strengthening according to the NSM, and the other, forming a certain angle with the previous part, is applied according to the ETS technique. Both parts are connected by a transition zone that provides an anchorage resisting mechanism to avoid premature debonding and concrete rip-off (Fig. 1). The first and last authors of this work are the inventors of this product and technique (Barros and Dourado 2016). The effectiveness of the first generation CutInov has already been demonstrated on the punching of RC slabs (Barros et al. 2017) and on the flexural strengthening of RC balconies (Barros et al. 2022). Analytical and numerical models have shown the development of a relatively high gradient and complex stress field in the transition zone when a CutInov is functioning as a strengthening reinforcement of an RC element (Nonato et al. 2019). This combined with a certain decrease of the tensile strength of this region due to the technology adopted on the production of the first generation of CutInov has caused the tendency for a premature rupture of this CutInov at this zone.

In this work, a second generation of CutInov reinforcement is used to assess its potential for strengthening simultaneously in flexural and shear RC beams of T cross-section.

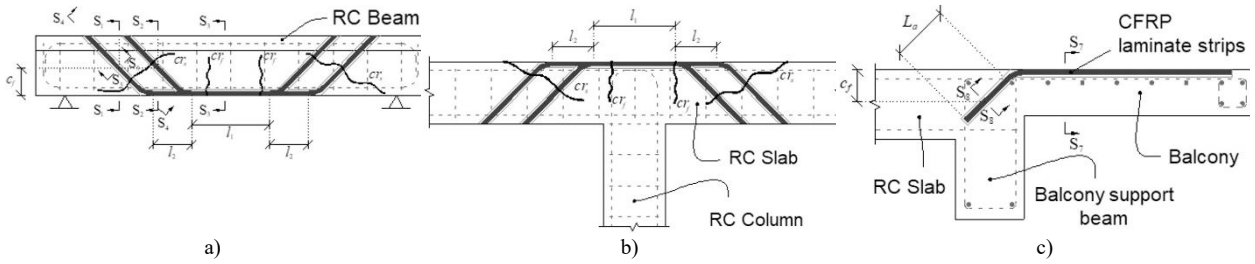


Fig. 1. Potential application of CutInov on: a) Simultaneous flexural and shear strengthening of RC beams; b) Simultaneous flexural and punching strengthening of RC slabs; c) Flexural of RC balconies.

2. Experimental program

2.1. Group of beams, strengthening configurations, and procedures

The experimental program is formed by three beams, whose particularities are represented in Fig. 2: a reference beam (Ref) and two beams strengthened with three CutInov CFRP bars (3CI and 3CI_A) with the geometry indicated in Fig. 2. The unique difference between these two beams is that 3CI_A has fan-type CFRP anchors (S&P C-Anchor) close to the transition zone of the CutInov CFRP. The three beams have a flexural reinforcement ratio of 0.52% and a shear reinforcement ratio of 0.09%.

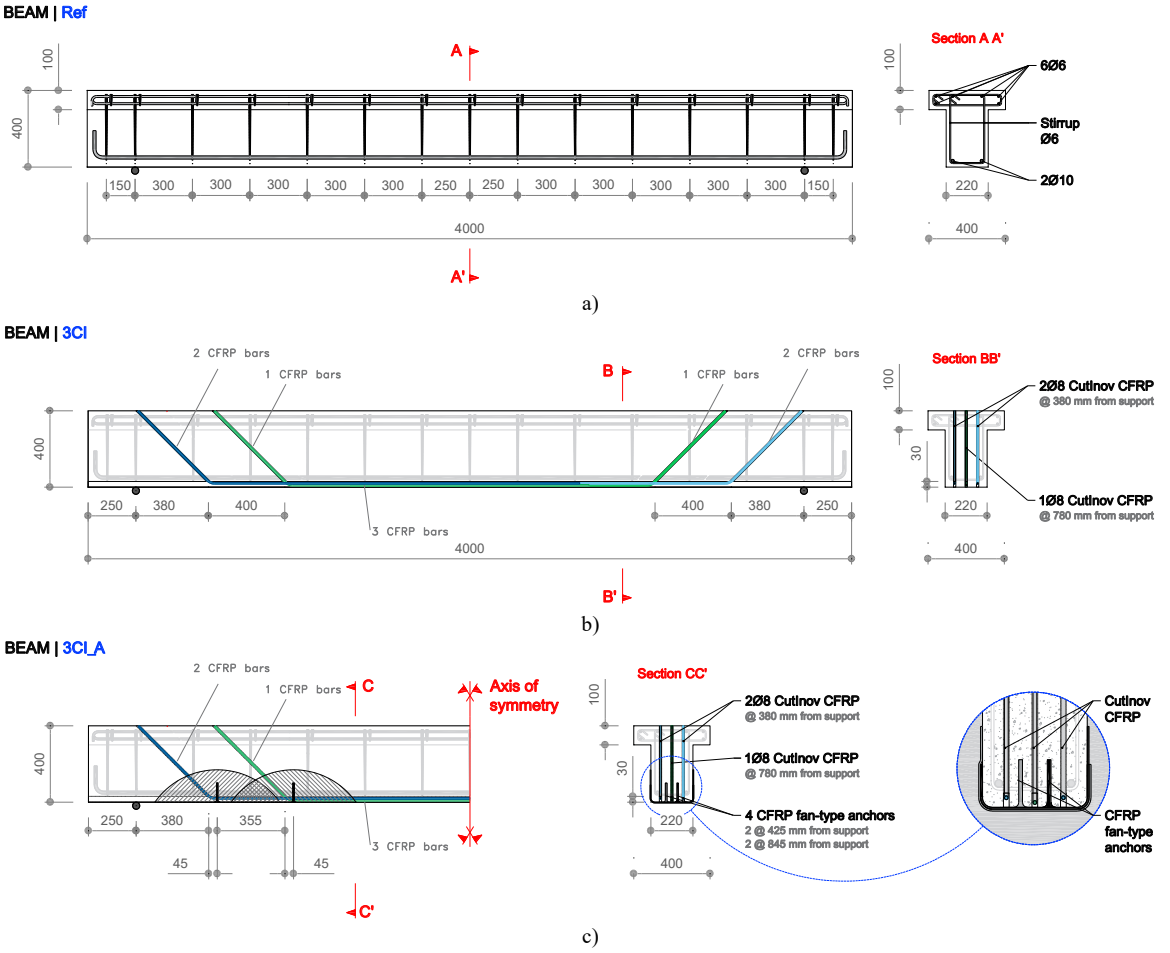
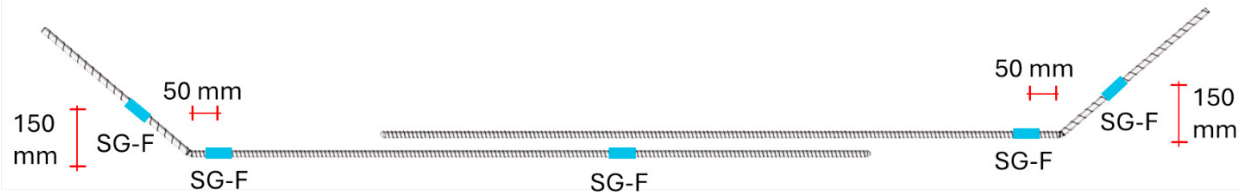
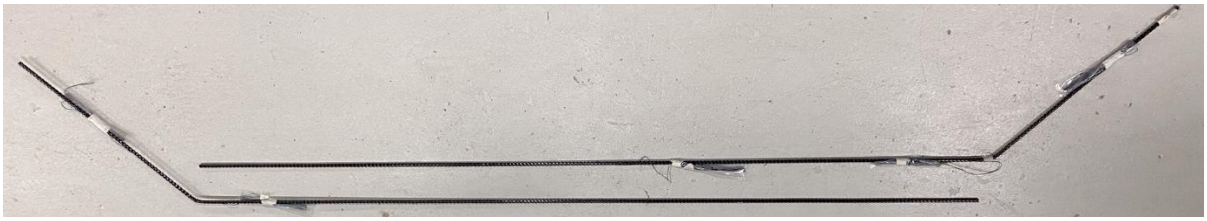


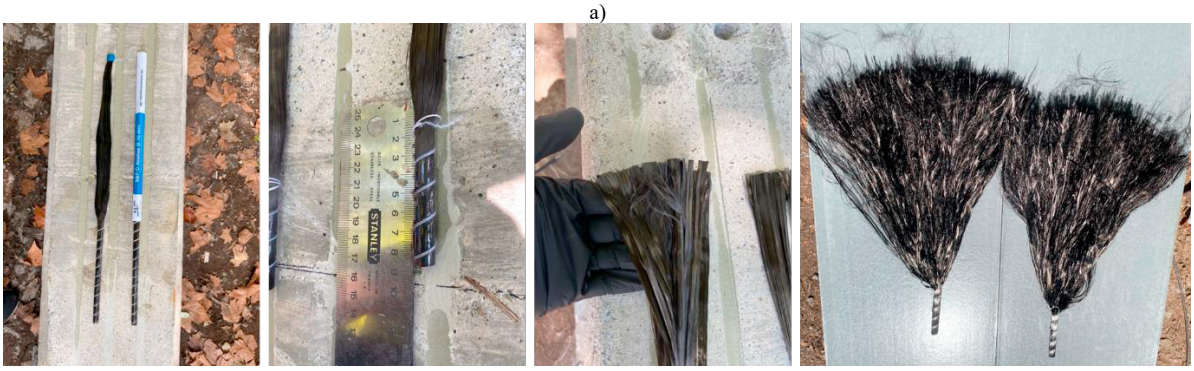
Fig. 2. Geometry of the beams, steel reinforcements, and strengthening configurations: a) reference beam (Ref); Strengthening beam b) without and with S&P C-Anchors close to the transition regions of CutInov reinforcements (3CI, 3CI_A). Note: All units are in [mm].

The geometry of the CutInov CFRP bars and the S&P C-Anchors are depicted in Fig. 3. The CutInov CFRP bars have a diameter of 8 mm and helical wrapping formed by Polyester fibres. The part of the CutInov CFRP bars applied according to the ETS technique has an inclination of 45° relative to the other part of these bars, which became disposed parallel to the longitudinal axis of the beam when applied to strengthen the beam.





a)



b)

Fig. 3. Geometry of a) CutInov CFRP bars (SG-Strain Gauges); and b) S&P C-Anchors.

2.2. Properties of the materials

By testing 3-cylinder specimens at 180 days of age (when the beams were tested) according to NP EN 12390–3:2011 and NP EN 12390–13:2014, an average compressive strength of 32 MPa and an average Young's modulus of 28.1 GPa were obtained. Steel bars of 6-, 10-, and 16-mm diameter (ϕ) were adopted as reinforcements of the tested beams. By executing tensile tests according to NP EN ISO 6892-1:2016, an average yield stress was obtained for these bars: 627 MPa for the ϕ6 mm; 531 MPa for the ϕ10 mm; 542 MPa for the ϕ16 mm. The tensile properties of the CutInov CFRP bars were assessed by performing tensile tests following the ISO 527-5 recommendations. An average modulus of elasticity of 150 GPa, an average ultimate tensile strength of 2382 MPa, and an average ultimate strain of 19.3‰ were obtained.

2.3. Strengthening procedures

The main strengthening steps of 3CI and 3CI_A beams are shown in Fig. 4. Before the application of CutInov bars on the beams, strain gauges (SG) were installed on the surface of these bars according to the schematic representation in Fig. 2. The holes and grooves were first executed according to the predefined plan (Fig. 4.1). In the inclined parts, the holes have completely crossed the section. After cleaning the holes and grooves with compressed air, the grooves were then filled with epoxy S&P 220 HP up to 20–30 mm of the holes (Fig. 4.2). The bars were then installed in their final position (Fig. 4.3), with their horizontal part (NSM) involved by the epoxy and cured to attain a hardened state. The holes were then filled with epoxy S&P 55 (Fig. 4.4). For the installation of the S&P C-Anchors, holes of 14 mm diameter and 100 mm depth were executed at approximately 45 mm from the transition zone of the CutInov bars (Fig. 2c, Fig. 4.6). To avoid stress concentration on the borders of the holes and on the edges of the cross-section covered by the fan, these borders were rounded with a radius higher than 30 mm (Fig. 4.6 and 4.7). The holes were cleaned

with pressured air (Fig. 4.8) and filled with VT-HP adhesive, whereas epoxy S&P 55 (Fig. 4.10) was applied on the concrete substrate to be covered by the fan. The rod part of the S&P C-Anchor, with a diameter of 10 mm (Fig. 4.9), was inserted into the corresponding hole, while the fan part was bonded by adding an extra layer of epoxy S&P 55 on its external surface (Fig. 4.10).

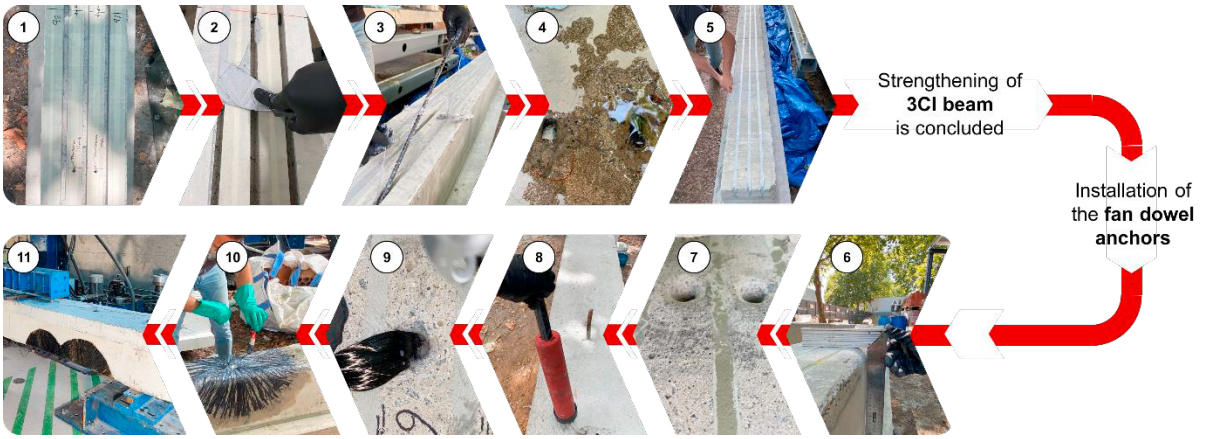


Fig. 4. Strengthening procedures for the 3CI and 3CI-A beams.

2.4. Test setup and monitoring system

Fig. 5 shows the loading and support conditions of the tested beams, as well as the monitoring system: displacement transducers LVDT1 to LVDT5 to measure the beam´s deflection, and LVDT6 and LVDT7 for recording the strains at the level of the steel flexural reinforcement. LVDT1 to LVDT5 are supported on an aluminium bar fixed in the geometric centre of the beam's sections over beam's supports to do not being registered parasitic deflections. Fig. 6 includes photos of the beam's test setup and monitoring system.

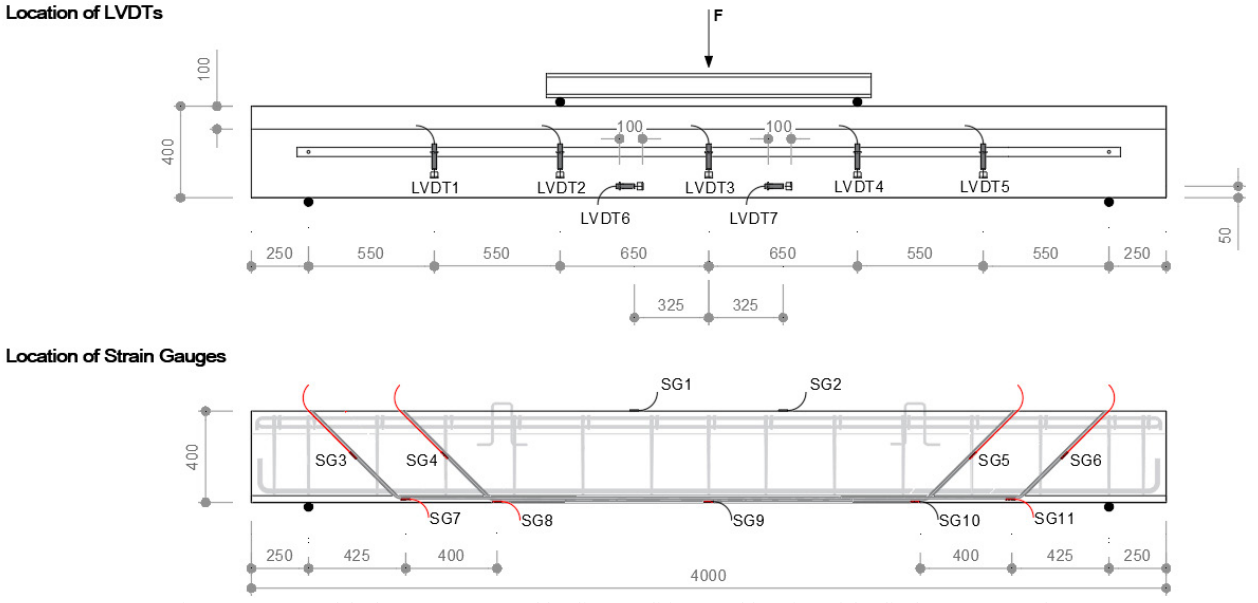


Fig. 5. Geometry of the beams, support and loading conditions, and location of the displacement transducers.



Fig. 6. Photographs of the test setup and monitoring system adopted in the experimental programme.

2.5. Results

Fig. 7 shows the total load versus the mid-span deflection registered in the tested beams. It is verified that up to crack initiation, the three beams presented the same response. As expected, the reference beam failed in bending. After crack initiation, both strengthened beams presented much higher stiffness and load carrying capacity than the reference beam. Up to close the service limit deflection (L/250=14 mm), the two strengthened beams developed similar response, showing that the S&P C-Anchor did not provide significant contribution for the behaviour of the beam up to this stage. However, above this SLS deflection, damage started to be concentrated in the transition zones (Fig. 8). In the case of the 3CI beam, a larger decrease of stiffness occurred, and at a deflection of about 30 mm, the tensile rupture at the transition zone of the CutInov reinforcements led to an instantaneous loss of load carrying capacity, which became equal to that of the reference beam. Compared to the Ref beam, an increase of 55%, 71%, and 79% was registered in the 3CI beam at, respectively, the service load (at SLS deflection), yield initiation of the flexural steel reinforcement, and maximum load. In a previous work with the same type of beam (Barros et al. 2016), which was flexurally strengthened with 3 NSM-CFRP laminates of 1.4×20 mm^2 cross section, it failed in shear at a load of about 210 kN. Since the maximum load of 3CI exceeded this load with a premature failure by tensile rupture at the transition zone of the CutInov bars, the inclined parts of these bars were effective in the shear strengthening of the beam. Fig. 7 shows that the S&P C-Anchor had a pronounced contribution to the stiffness and load-carrying capacity of the beam above the SLS deflection. In fact, when compared to the results on the Ref beam, an increase of 61%, 95%, and 117% was registered in the 3CI_A beam at, respectively, the service load, yield initiation of the flexural steel reinforcement, and maximum load. This beam failed by tensile rupture of the CutInov CFRP bars (Fig. 8c) out of the transition zone, at a deflection of about 50 mm, above which the load carrying capacity of this beam became equal to that of the reference beam.

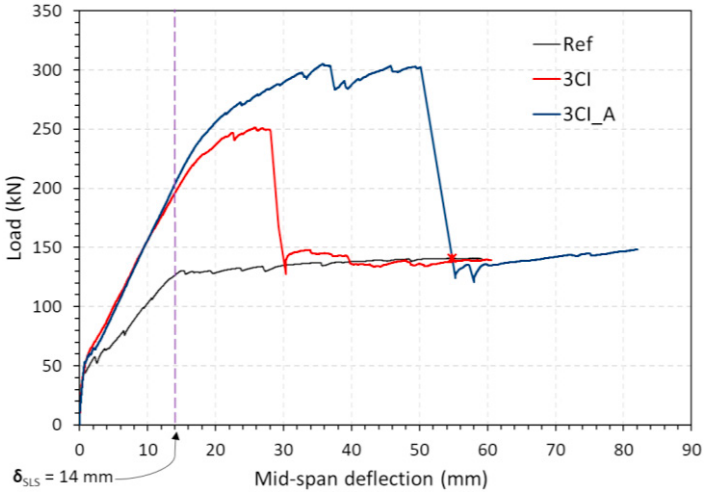


Fig. 7. Total load versus mid-span deflection (recorded by LVDT3) in the tested beams.

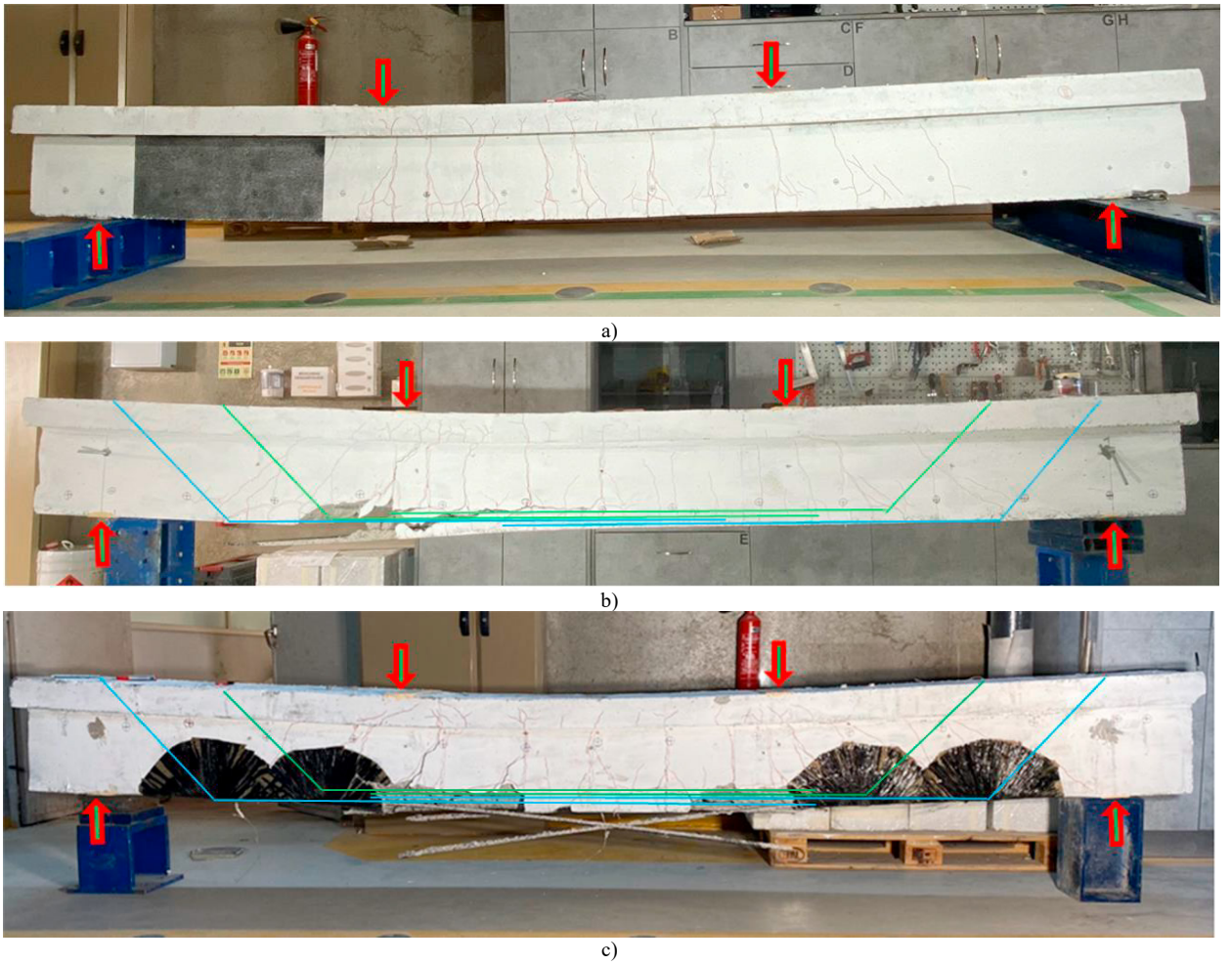


Fig. 8. Failure modes of beams. a) Ref; b) CI; c) CI-A

4. Conclusions

This paper presents an experimental programme of RC beams of T cross-section for assessing the potential of CutInov CFRP bars for the simultaneous flexural and shear strengthening of this type of structural element. The programme was composed of a reference beam (Ref) and two beams strengthened with three CutInov bars, one with a fan-type CFRP anchor, S&P C-Anchor (3CI_A), and the other without this type of anchors (3CI). From the obtained results, it was concluded that:

1) Compared to the results obtained in the Ref beam, an increase of 55%, 71%, and 79% was registered in the 3CI beam regarding the, respectively, load at a deflection corresponding to serviceability limit state conditions, $\delta_{SLS}=L/250=14$ mm, (F_{SLS}), load at yield initiation of the flexural steel reinforcement (F_{sy}), and maximum load (F_{max}).
2) The 3CI beam failed by premature tensile rupture at the transition zones of the CutInov bars, but at a deflection of about 2 times δ_{SLS}, when the flexural steel reinforcement had already experienced significant incursion on its elasto-plastic regime. Therefore, significant ductility was assured.
3) Compared to the results obtained in the Ref beam, an increase of 61%, 95%, and 117% was registered in the 3CI_A beam regarding the, respectively, F_{SLS}, F_{sy}, and F_{max}.

4) The S&P C-Anchors were very effective not only in increasing all previous force indicators but also in avoiding premature rupture of the CutInov bars at their transition zone. In fact, these bars ruptured out of the transition zone when the beam's deflection was about 4 times the δ_{SLS}; therefore, these anchors contributed for a significant increase of the ductility of the beam.

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