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COMPUTER AIDED DESIGN OF FRP STRENGTHENING FOR EXISTING RC BEAM-COLUMN JOINTS

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Abstract

Existing reinforced concrete buildings in the Mediterranean area are vulnerable to seismic actions due to the lack of proper seismic detailing. Different retrofit solutions are available on the market and effective in improving the seismic performances. However only few of them can be easily applied in-field with a reduced impact for the occupants. In this context, fiber-reinforced polymers gained popularity because of their demonstrated effectiveness, ease of installation, reduced total cost and durability. This had a significant impact on the current market of retrofitting worldwide with increasing number of applications of FRP strengthening. In this context this research work proposes a novel software tool to drive practitioners through the computer aided design of FRP strengthening for existing beam-column joints. It relies on the design approach suggested in the fib bulletin 90 including recent development in terms of novel techniques to minimize the impact to the occupants. Local strengthening or global seismic retrofitting can be used and the increasing seismic performance can be easily quantified

Keywords: Joint FRP, Seismic, retrofitting, reinforced concrete, shear.

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1 INTRODUCTION

Recent devastating earthquakes pointed out the poor seismic performance of the existing building stock and the urgent need for effective retrofitting measures that can applied at regional scale. Concerning the existing reinforced concrete (RC) buildings, the lack of proper seismic details often led to the premature shear failure of structural members. This may significantly compromise the global building response resulting in the collapse of a portion or of the entire building. Post-earthquake observations showed number of failures at level of beam-column joints due to lack of transverse reinforcement and poor-quality concrete (see Fig. 1). This could be related to the increasing shear demand in the joint panel due to frame behavior under earthquake loads or to the shear demand at the top of the bottom column due to the action of infills [1].

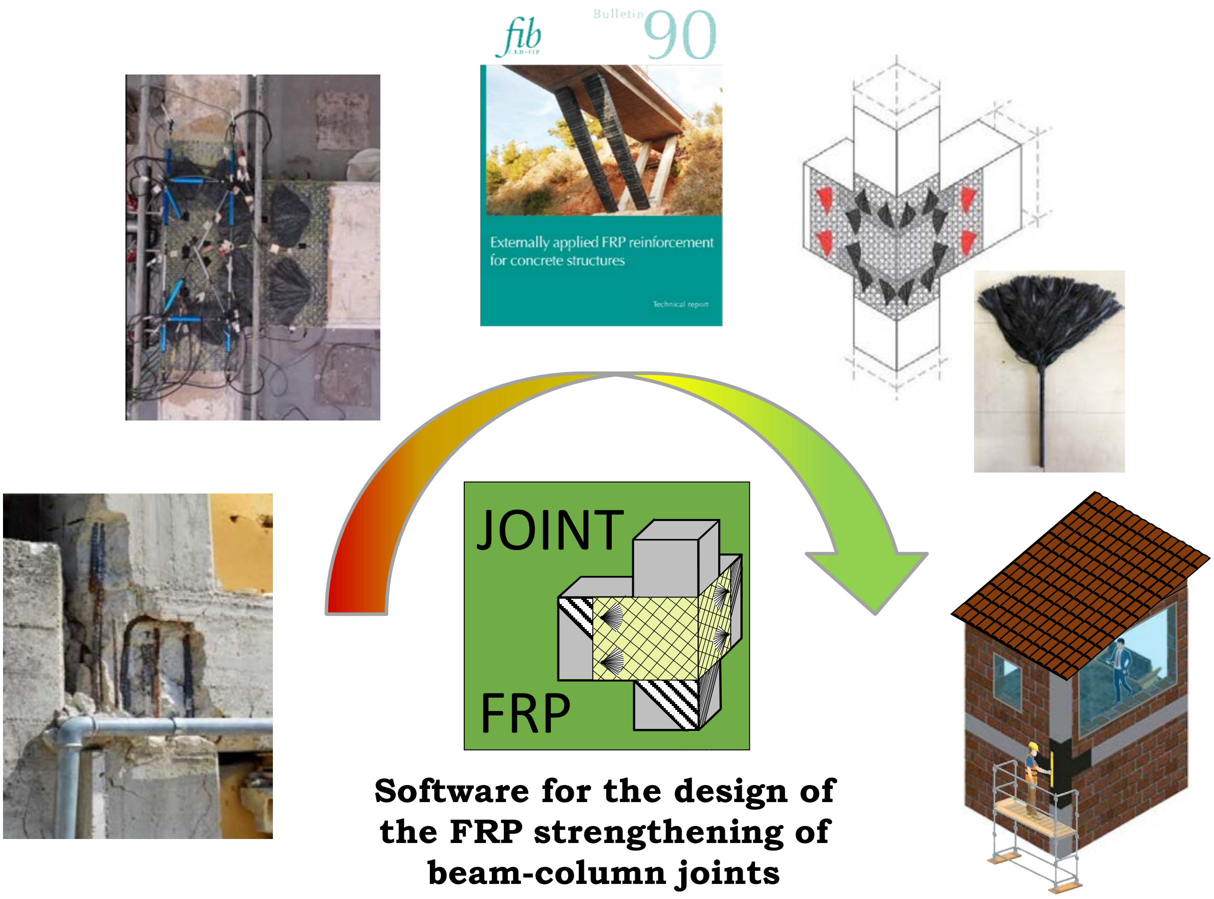


Figure 1: JOINT FRP field of application.

In this context, experimental tests and analytical studies demonstrated the effectiveness of composite materials (e.g. fiber reinforced polymers, FRP, textile reinforced mortar, TRM) increasing the seismic performance of joint subassemblies or entire structural systems [2–5]. Despite of the significant advantages in the seismic strengthening of existing RC buildings, seismic risk mitigation strategies at regional scale are difficult to be implemented during peacetime. This is because the significant cost of intervention and of the interruption of building functionality for some months discourages the occupants in undertaking seismic retrofitting. However, seismic losses can be detrimental in terms of fatalities and economic impact at regional/national level. Thus, retrofit solutions with a reduced cost and low level of disruption may favorites the actuation of seismic risk mitigation strategies on large scale. This is the motivation of the DPC-ReLUIS research project that dedicated the WP5 to “Fast and integrated retrofit interventions”. Withing the framework of this project experimental tests and analytical studies were conducted to develop and validate effective retrofit solutions with a minimum impact on the occupants [6]. A practice-oriented design procedure was later developed to help practitioners in the design of FRP strengthening of the joint panel by using strengthening layouts that can be applied from the exterior of the building. This procedure has been later implemented in a user-friendly software named JOINT FRP [7] distributed free of charge with the scope of have a large diffusion within practitioners.

This paper present and discusses the analytical model and the computational algorithm at the base of the software. The design strategies, input parameters and design variable of the FRP strengthening system are illustrated. A focus on the design of mechanical anchors useful to guarantee the installation from the exterior of the building is proposed. An application to a case study building by using two different design strategies is presented.

2 DESIGN APPROACH

The design approach implemented in the software was originally proposed by Del Vecchio et al. [8] and then adopted by the fib bulletin 90 [9]. It allows to design the shear strengthening of the joint panel targeting specific requirements in terms of principal tensile stresses. It accounts for the axial load and concrete contribution to the principal tensile stresses and enabling determination of the required jacket thickness with fibres oriented in multiple directions (multi-axial fabrics with fibres at 0°, 90°, ±45°). This approach is based on the use of the principal tensile stress derived combining the joint shear stress $v_{j,h} = V_{j,h}/b_c \cdot h_c$ and the axial stress $f_a = N/b_c \cdot h_c$. The horizontal shear force acting in the joint, $V_{j,h}$ is derived from Eq. (8-50) or Eq. (8-53) and N is the axial load acting on the top column. The adopted design approaches comply with the Italian building code (D.M. 17 January 2018 and Circolare n.7 21 January 2019) and with the recent fib bulletin 90 (2019) for the strengthening of existing structures by means of FRP. Two different design strategies can be selected. A “Local strengthening” design approach, as defined in the §5.1.3 of the EN 1998-3:2005 and fib bulletin 90. Local interventions are those that increase the deformation capacity of deficient components – by suppressing shear failures – without affecting the overall structural stiffness which controls the seismic demand. The design approach named “Based on selected internal actions” allow to compute the joint shear demand and perform the safety check in terms of principal tensil stress in the joint panel based on the internal actions provided as input. The latter can be used in the desing of a global retrofit intervention where a 3D building models is used to perform a seismic analyses at specified target of the seismic action. The different sections of the software are described in the following.

3 THE SOFTWARE

The software is conceived as a design support to be used alone or together with other tools for structural analyses. For this purpose, all the input parameters, design variable and output are plotted in one window that can be opened on the screen and minimized during the use of other software. It relies on a click and launch architecture programmed in C# [10]. The main window is reported in Fig. 2 while details of the different sub-section are discussed in the following. It is composed of 13 sub-sections with different objectives: input of the joint variable (section 1-6), safety check of the as-built joint in terms of tensile strength (section 7), input of FRP design variables (section 8), safety check of the FRP strengthened joint (section 9),

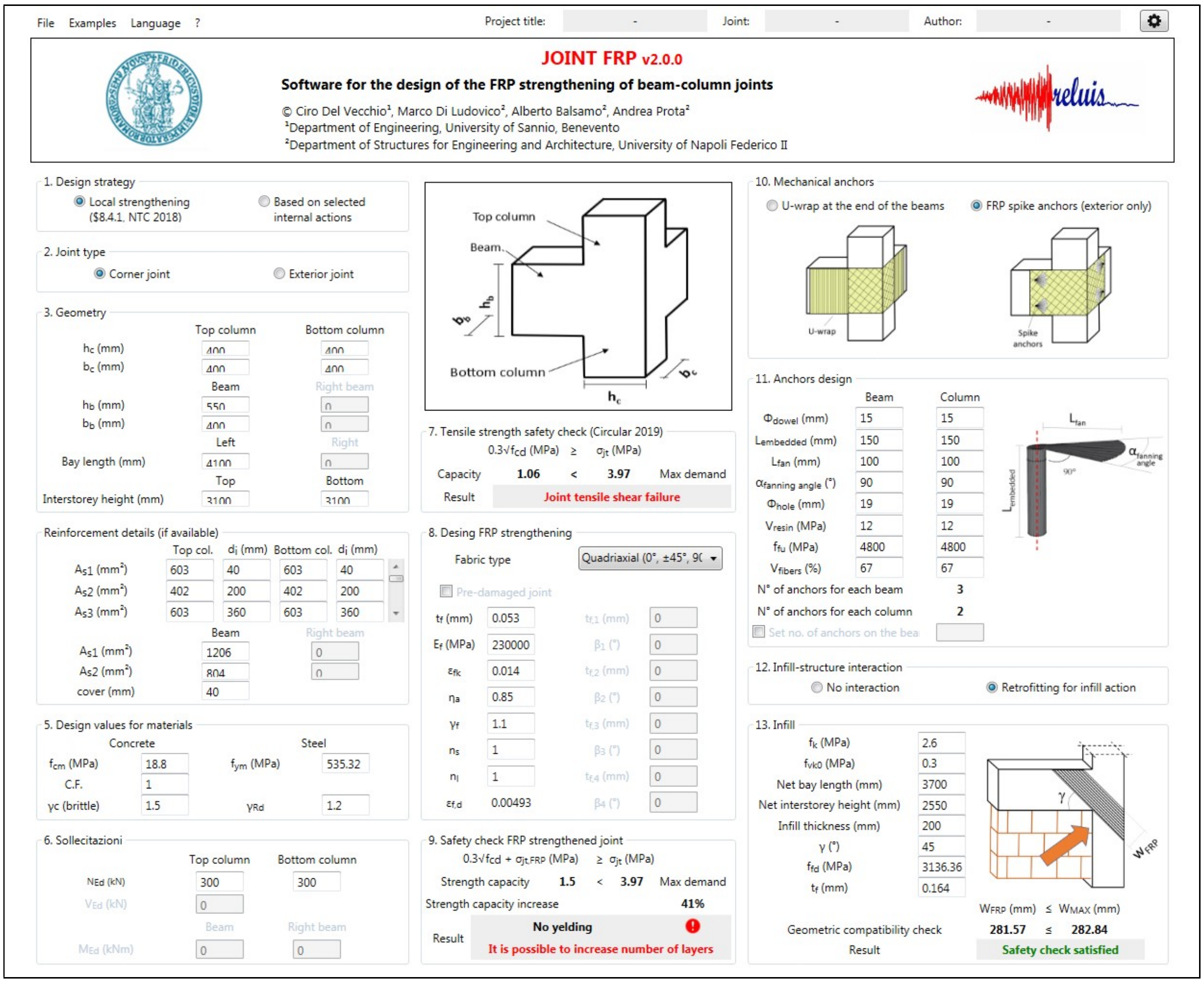


Figure 2: GUI of the software JOINT FRP.

design of the mechanical anchors (sections 10-11), design of the FRP strengthening system to resist the infill action (sections 12-13).

3.1 Input

A clos-up on the sub-sections dedicated to the selection of the design strategy (section 1), selection of the joint type (section 2), to define the geometry of the joint panel (section 3), the reinforcement details (section 4), the material properties (section 5) as-well-as the actions on the framing members (section 5) is reported in Figure 3. The first section allows the selection of the design strategy between a local strengthening and a global retrofit (namely "Based on selected internal actions"). Then the used should select the type of unconfined joint to be analyzed between "Corner joint" where there is only on beam framing in the joint panel or "Exterior joint" where two beams are available. The user may also analyze "knee joints" where only the bottom column is available. In this case the geometry and actions at the top column should not be defined and the software considers this joint as a knee joint.

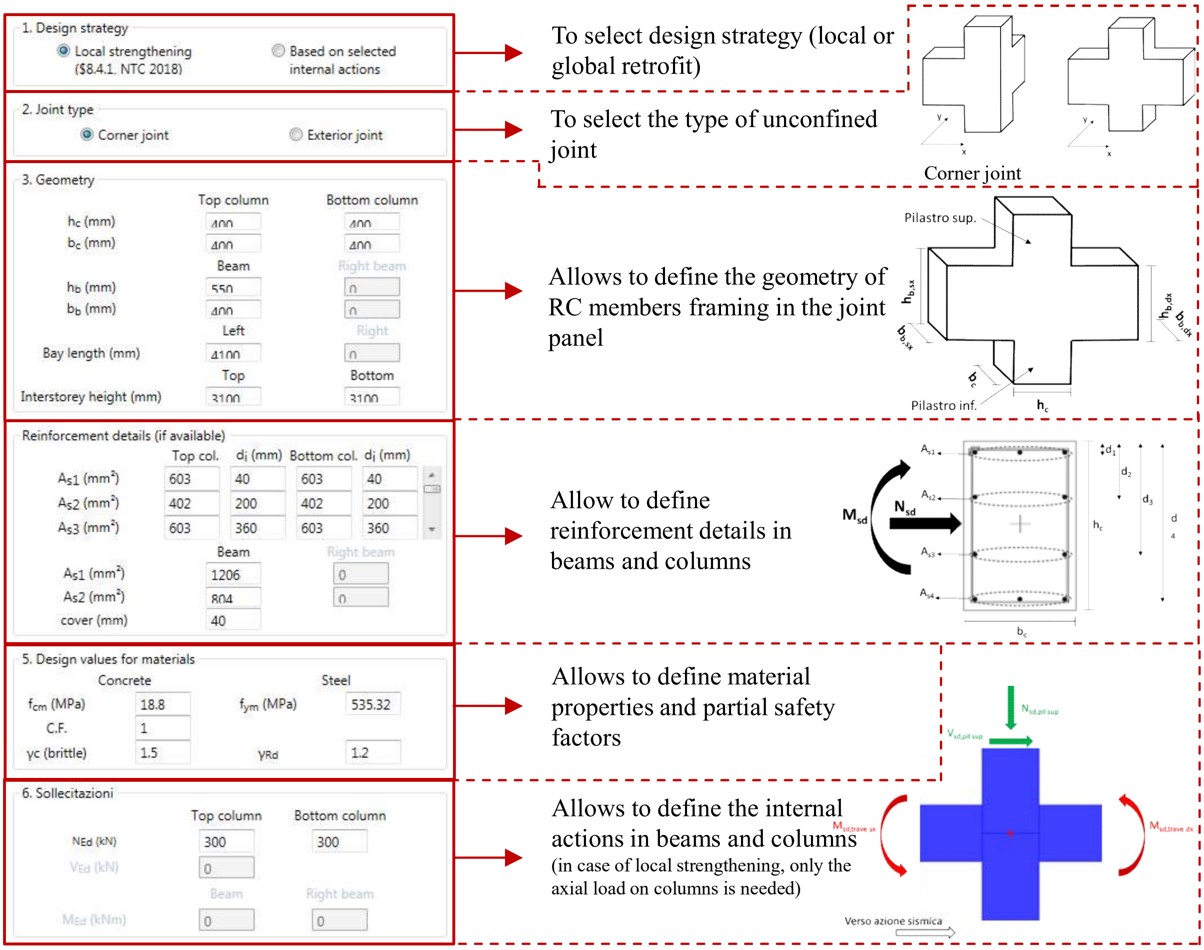


Figure 3: Description of the input sections of the software.

3.2 FRP strengthening of the joint panel

Section 7 perform the safety check at the life safety limit state in terms of principal tensile strength of the joint panel. It considers the joint panel at the first cracking as the ultimate limit state according to the Italian building code [11] and Eurocode 8 [12].

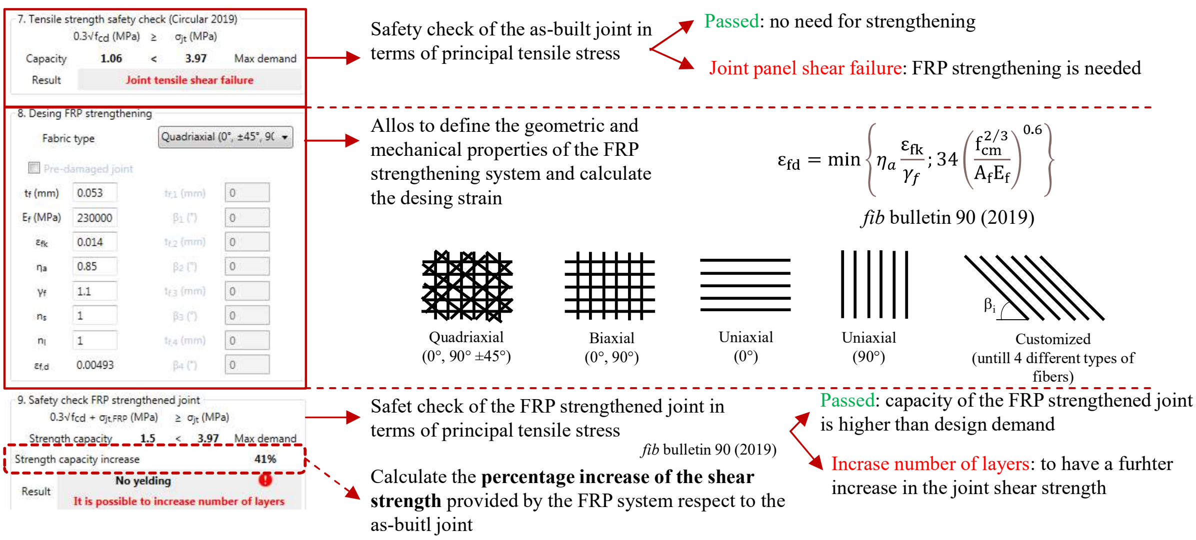


Figure 4: Safety checks and design parameters of the FRP strengthening.

In case that the joint shear strength provided by the concrete alone is not capable of sustain the joint shear demand, the software suggest the use of an FRP strengthening. The input parameters to define the strengthening layout can be typed in section 8 (see Fig. 4). In field applications, the FRP fibers are generally applied in the horizontal and/or vertical direction or in multiple directions in the case of multi-axial fabrics (0°, 90°, ±45°). Thus, in order to simplify the calculation of the equivalent FRP area, $A_{f,eq}$, several equations have been developed for the most common applications: Uniaxial fabric with fibers in the direction of beam axis (0°) or column axis (90°), Bidirectional fabric with fibers in the direction of beam and column axes (0°, 90°), Quadriaxial fabric with any fibers in the direction of beam (0°) and column (90°) axes and ±45°. Then the software calculate the design strain with the formulation proposed by the fib bulletin 90 and calibrated by Del Vecchio et al on a dataset of experimental tests on RC beam-column joints strengthened with FRP systems.

3.3 Mechanical anchors

Special details at the ends of the FRP strengthening need to be provided in order to secure the jacket against debonding (e.g. mechanical anchors or U-wraps). When the FRP reinforcement is not properly anchored, FRP strengthening shall not be considered effective.

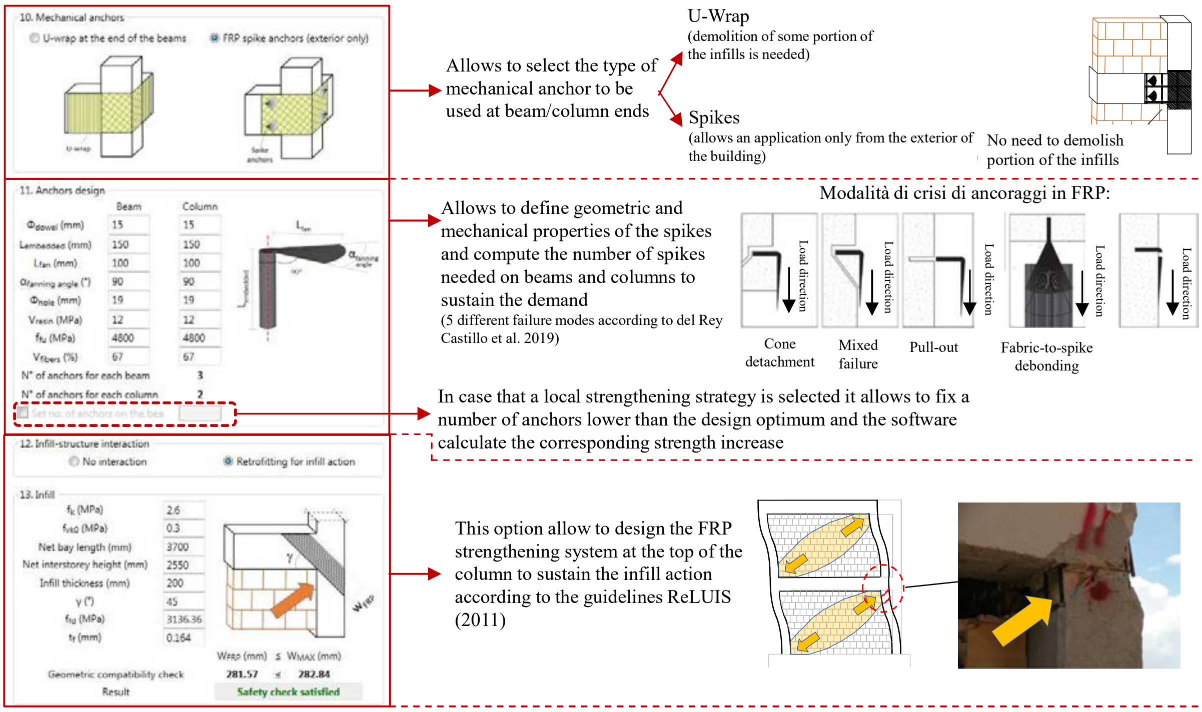
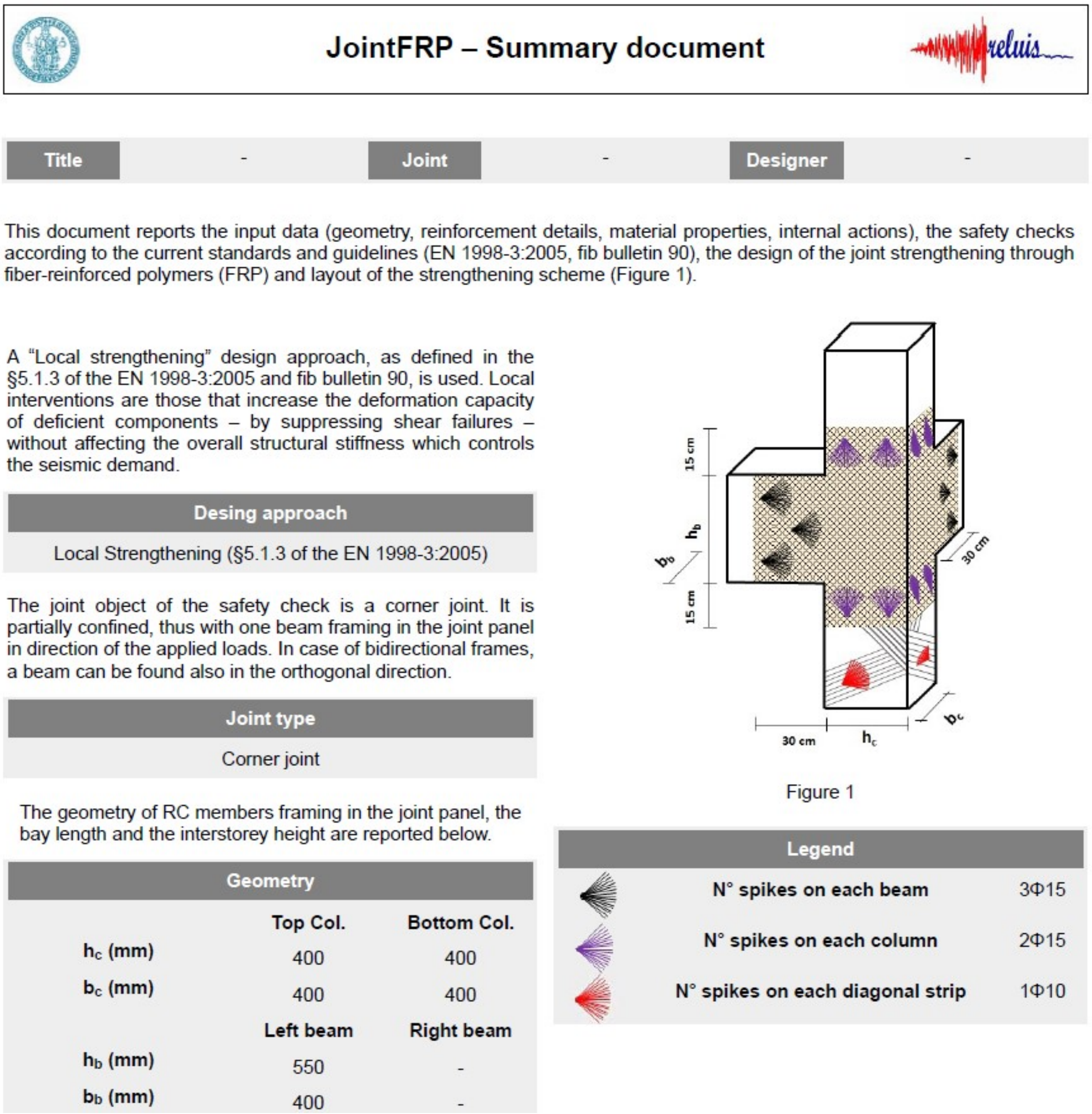


Figure 5: Design of the mechanical anchors and of the strengthening system to resist the infill action

As described in Fig. 5, the use of FRP spike anchors allow to minimize the level of disruption guaranteeing the application from the exterior side of the building. The design of FRP spikes is performed considering five possible failure modes as indicated in del Rey Castillo et al. [13] and considering the low effectiveness of carbon fiber when loaded in the direction orthogonal to the fiber axis as demonstrated by Mahrenholtz et al. [14].

3.4 Design report

At the end of the design procedure the, the user may decide to print (by mean of a real or a virtual printer) a summary document of the design procedure. This document reports the input data (geometry, reinforcement details, material properties, internal actions), the safety checks according to the current standards and guidelines (EN 1998-3:2005, fib bulletin 90), the design of the joint strengthening through fiber-reinforced polymers (FRP) and layout of the strengthening scheme. An example of the front page of the report is depicted in Fig. 6.



JointFRP – Summary document

Title	-	Joint	-	Designer	-

This document reports the input data (geometry, reinforcement details, material properties, internal actions), the safety checks according to the current standards and guidelines (EN 1998-3:2005, fib bulletin 90), the design of the joint strengthening through fiber-reinforced polymers (FRP) and layout of the strengthening scheme (Figure 1).

A "Local strengthening" design approach, as defined in the §5.1.3 of the EN 1998-3:2005 and fib bulletin 90, is used. Local interventions are those that increase the deformation capacity of deficient components – by suppressing shear failures – without affecting the overall structural stiffness which controls the seismic demand.

Desing approach
Local Strengthening (§5.1.3 of the EN 1998-3:2005)

The joint object of the safety check is a corner joint. It is partially confined, thus with one beam framing in the joint panel in direction of the applied loads. In case of bidirectional frames, a beam can be found also in the orthogonal direction.

Joint type
Corner joint

The geometry of RC members framing in the joint panel, the bay length and the interstorey height are reported below.

Geometry		
	Top Col.	Bottom Col.
h_c (mm)	400	400
b_c (mm)	400	400
	Left beam	Right beam
h_b (mm)	550	-
b_b (mm)	400	-

Figure 1

Legend		
	N° spikes on each beam	3Φ15
	N° spikes on each column	2Φ15
	N° spikes on each diagonal strip	1Φ10

Figure 6: Front page of the design report produced by the software.

4 CASE STUDY

To show to the reader the capabilities of the proposed software helping researchers and practitioners in conducting computer aided design of FRP strengthening of existing RC beam-column joints a case study building is selected. First the seismic performance is assessed in the as-built configuration and then the FRP strengthening scheme is designed by using both local strengthening and global retrofit design strategy.

4.1 Local strengthening

The local strengthening design strategy aims at increasing the seismic performance of the building bypassing the premature brittle failures by using strengthening solutions that do increase the stiffness and masses of the building. The result of the local strengthening in terms of strength increase of the joint subassembly are reported in Fig. 7 along with a sketch of the strengthening layout.

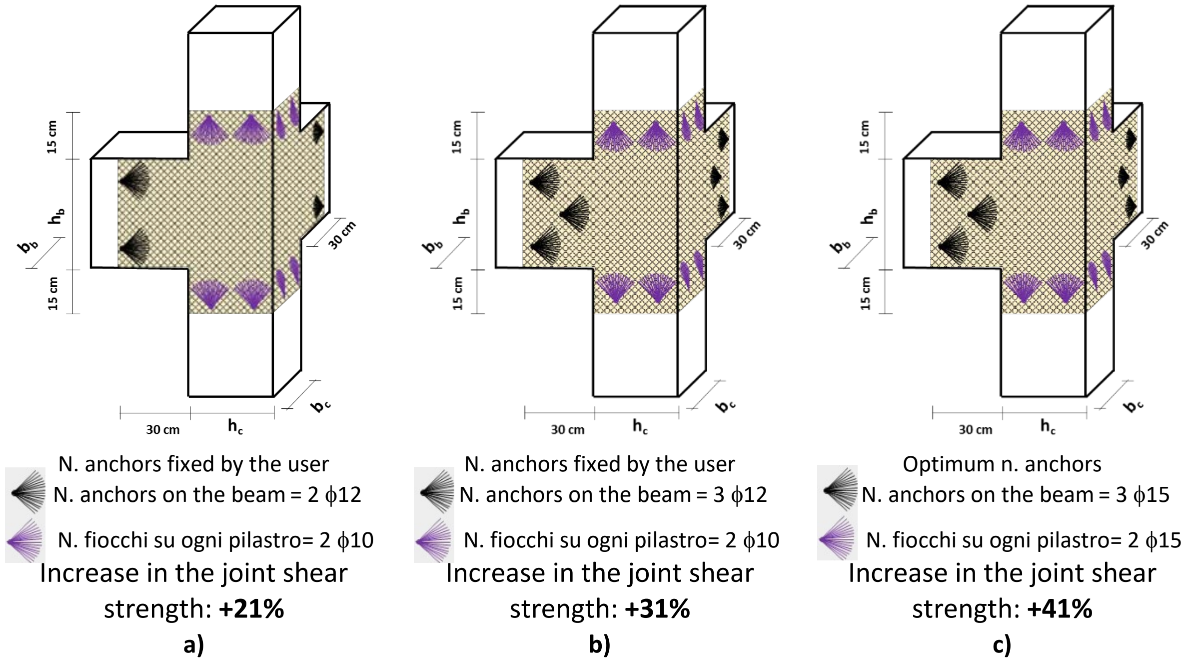
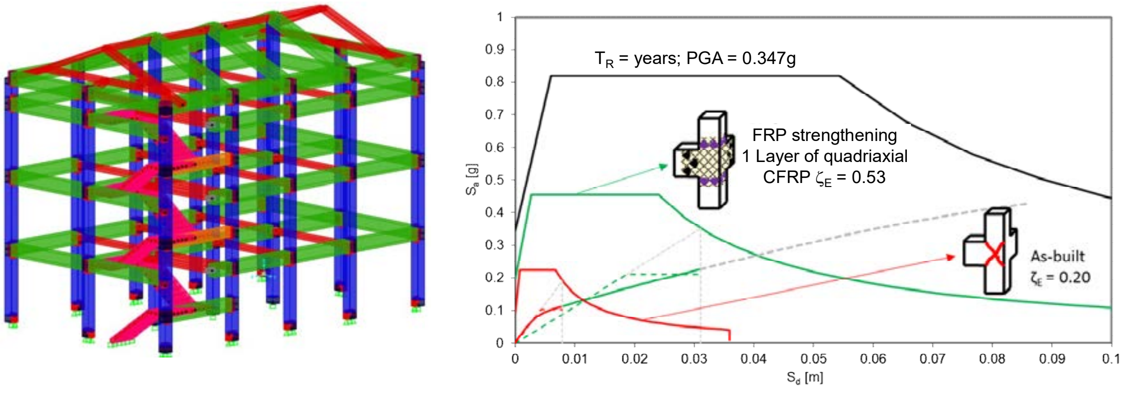


Figure 7: Increase of the joint shear strength as function of the n. of anchors: a) 2 ϕ 12 on the beam; b) 3 ϕ 12 on the beam; c) 3 ϕ 15 on the beam.

The optimum number of anchors that can carry the entire design strain in the FRP quadriaxial fabric is the one reported in Fig. 7b. the exercise of reducing the number of anchors is done to show to the reader the capabilities of the proposed software to account for the strength reduction due to a number of anchors lower than design optimum in case that the user is forced to the use of low number of anchors to minimize the cost of the intervention.

4.2 Global retrofitting

To assess the seismic performance of the entire building and design the FRP strengthening within a global design strategy aimed at the achievement of a specific safety index, a FEM model of the building is needed. More details on the modelling strategy and on the building geometry, mechanical properties and reinforcement are reported in Del Vecchio et al. [15]. The results of the seismic retrofitting by using a global design strategy are reported in Fig. 8



a) b)

Figure 8: Seismic performance assessment of the entire structural system: a) building 3D model; influence of the FRP strengthening in the ADRS spectrum.

The FRP strengthening of the unconfined joint panels avoids the premature shear failures promoting a more ductile failure mode. Such in increase of the local strength of joint subassemblies result in a significant increase of the global seismic performance moving from a ratio of the PGA_c/PGA_d of 0.20 to 0.53.

5 CONCLUSIONS

This paper presents and discusses the analytical model implemented in the user-friendly design software JOINT FRP enabling researchers and practitioners to simply design the FRP strengthening of poorly detailed RC beam-column joints. It relies on the analytical model recently adopted in the fib bulleting 90 and it includes recent progresses in the design of strengthening intervention with a minimum level of disruption to the occupants. The main future can be summarized as follows:

- The design of the FRP strengthening system can be done within the framework of a local strengthening or a global retrofitting and considering corner, exterior and knee joints;
- It relies on the principal stress approach to calculate the capacity of the as-built joint (concrete alone), to consider the influence of the axial load and the contribution of the FRP strengthening to the principal tensile stress;
- It accounts for different fiber types (CFRP and GFRP); different strengthening layouts with a variable amount of fibers on the joint panel, number of layers, number of strengthened sides (to account of the presence of the orthogonal beam) and the inclination of fibers (or multiple inclinations); continuous reinforcement or strips; strengthening system applied on a damaged and lightly repaired joint panel; adoption of mechanical anchors;
- A summary document with details on the input data (geometry, reinforcement details, material properties, internal actions), the safety checks according to the current standards and guidelines (EN 1998-3:2005, fib bulletin 90), the design of the joint strengthening through fiber-reinforced polymers (FRP) and layout of the strengthening scheme is produced at the end of the design.

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