# Strengthening and Repair with Advanced Materials and Hybrid Techniques for Increased Resilience of RC Structures with the Use of Pseudo-dynamic 3d Finite Element Analysis

Theodoros Rousakis(✉)

Department of Civil Engineering, School of Engineering, Democritus University of Thrace, Xanthi, Greece
trousak@civil.duth.gr

**Abstract.** This paper presents a critical review of advanced retrofit materials and recent techniques that may be utilized in earthquake resistant redesign of reinforced concrete structures to increase their resilience and safety. It also discusses some open design recommendation-related issues that may jeopardize structural member resilience. It reveals the potential of the Elastic Redistributable Uniform Confinement (ERUC) mechanism and concept and the contribution of relevant techniques in addressing some of the open issues. There is an urgent need for large scale dynamic experiments according to the fundamental 'design assisted by testing' procedure. Besides, the development of the framework for advanced dynamic 3-dimenional Finite Element (FE) modelling could support analytically these significant tasks. This study presents pilot pseudo-dynamic analytical studies on the Elastic Redistributable Uniform Confinement technique through external continuous spiral composite rope strengthening of concrete as well as on the FRP jacketing of RC columns. Three-dimensional FE modeling may help minimize required experimental validation of emerging techniques for seismic protection of brick infilled RC frames through highly deformable polymer joints or through externally bonded fiber grids with highly deformable polymers. Finally, it may help identify additional design parameters, enable further optimization of different hybrid retrofit techniques and enhance resilience and safety of concrete members.

**Keywords:** Resilience · Reinforced concrete · FRP · Dynamic · Finite element

## 1 Introduction

According to NAC (2012), resilience is multidisciplinary and interdisciplinary concept defined as "the ability to prepare and plan for, absorb, respond, recover from, and more successfully adapt to adverse events". McAllister (2016) reports ongoing activities of several communities all over USA related to resilience plans for critical infrastructure of high importance (see Fig. 1) against various hazards. San Francisco adopted the new Hub concept for its infrastructure (Hansen et al. 2008) while Boulder County published


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recently the Resilient design performance standard for infrastructure Moddemeyer et al. (2016) among else. Despite the significant progress, the resilience framework needs to be further developed and integrated. In the rest of the world and especially in Europe, resilience related planning and activities were rarely reported in the past while there are some very important ongoing initiatives through DRMKC (https://drmkc.jrc.ec.europa.eu/). It has already concluded its 'Science for Disaster Risk Management 2017: Knowing better and losing less' report (Poljansek et al. 2017) while the Science for DRM 2020 report has been recently published (Valles et al. 2020). Of course, resilience metrics, approaches and concepts have to be further developed at members' and systems' levels to better prioritize proactive actions in infrastructure as an integral part of the resilient society concept (Bocchini et al. 2014, Rousakis 2018).

Southeast Mediterranean region in Europe is a live laboratory with daily experiments in 1:1 scale to validate the resilience of existing structures, investigate vulnerabilities and conclude advanced approaches (Fig. 2).

**Fig. 1.** Resilience of critical infrastructure in communities. (adapted by McAllister (2016))

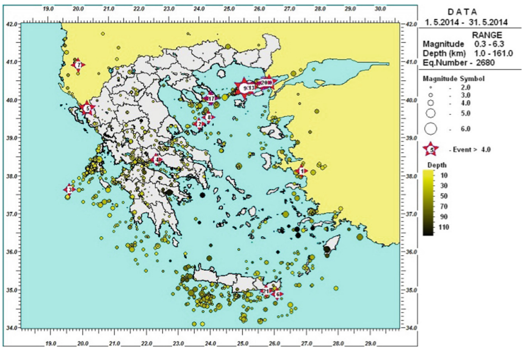



**Fig. 2.** Earthquake excitations at the most active region of Europe during 1 month period.

The level of existing knowledge is high and recent design codes for buildings are very efficient resulting in limited human loss in Europe. Yet, more than 900,000 people were lost and around 3.1 million buildings collapsed or heavily damaged during the 30 major earthquakes over only the past 20 years (USGS 2016). Given the heavy life loss and accompanied detrimental consequences, new concepts and techniques may help better address the necessary prevention steps.

In structural retrofit several innovative techniques have emerged recently involving advanced materials (Karantzikis et al. 2005, Triantafillou et al. 2006, Wu et al. 2008, Ilki et al. 2008, Janke et al. 2009, Tamuzs et al. 2006, Dai et al. 2011, Kwon et al. 2016, Rousakis et al. 2017, Rouka et al. 2017, Kwiecień et al. 2017, Padanattil et al. 2017, Ispir et al. 2018, Triantafyllou et al. 2019, Qin et al. 2019, Rousakis et al. 2020a, b among else). Rousakis (2018) highlights the unique inherent resilience features of square RC columns retrofitted with composite ropes, under seismic excitations. In Rousakis and Tourtouras (2014) external rope confinement of deficient RC columns under axial load, provided enormous axial strain ductility of concrete. The accumulated damages were redistributed through the nonbonded elastic rope (applied by hand or pretensioned), causing multiple steel bar buckling in different positions, variable bulging of the concrete core at different places and extensive deformations attributed to global buckling while maintaining the axial load capacity. Similar effects were evidenced in experiments of deficient square RC columns having hybrid externally bonded FRP and nonbonded composite rope confinement (Rousakis 2017, 2019). What is more interesting is the achievement of enormous axial strain ductility of concrete through adequate nonbonded basalt rope confinement (applied by hand or pretensioned). Again, despite the limited strain at failure of the basalt confining means, the RC column could maintain or increase the axial load capacity through strain redistribution of the nonbonded rope (both as standalone confinement or in hybrid FRP-basalt rope schemes). Therefore, nonbonded elastic rope confinement may provide unique resilient characteristic in the cyclic axial behavior of deficient RC columns to better resist axial loads against premature collapse. The resilient characteristics concern: a) the used materials itself being natural, nontoxic, recyclable and high temperature resistant (basalt with no use of resin) among else, b) the low sensitivity of the elastic composite rope in being damaged, c) the unique confining performance of nonbonded elastic rope, achieving axial load regaining even in cases of temporary load loss because of severe concrete damages or steel buckling or FRP jacket fracture through damage redistribution.

The abovementioned unique observed features constituted an illustrative resilience-mechanical analog. A new design concept was concluded towards enhanced inherent resilience of similar subsystems from a structural point of view (Rousakis 2018). Subsystems with weak component susceptible to fatal damage accumulation may achieve enhanced inherent resilience. This may be realized with uniform redistribution of damages inside the main bearing core mass (weak link) in the presence of suitable external confinement. This confinement needs to be elastic to not accumulate damage itself while being highly deformable and flexible. Further, it should be non bonded to develop friction with the core (not fixing) and to redistribute strain around and inside the core. In that case, total core mass restricted under confining action is always the maximum one. Suitable confining action may preserve damage-sensitive-restriction in a way that globalizes damage inside the core and makes the core again more uniform and more homogeneous in response. Thus, the Elastic Redistributable Uniform Confinement (ERUC) enables for advanced axial load carrying capacity which is crucial to avoid detrimental collapse. The general design concept developed herein is multidisciplinary and interdisciplinary and may be further generalized to cover different systems and scales. Concluding so far experimental findings ERUC concept (through spiral rope) provides beneficial damage redistribution effects even if the core material has geometric non-uniformities (as in square concrete sections) and includes a second component accumulating damage (i.e. slender steel bars or yielded stirrups or fractured FRP jacket) or all these together (see Rousakis and Tourtouras 2014, Rousakis et al. 2019).

This paper focuses on the suitable mathematical formulations at material, section, member and structure level and their interrelations in order to provide reliable models of RC members retrofitted with advanced materials and capture strain redistribution effects. In what follows, the existing design framework is presented, some of the identified open issues as well as suitable constitutive models to address urgent needs.

## 2 Structural Resilience at Reinforced Concrete Member and Frame Level

For retrofitted RC columns, the resilience may be interpreted as the ability to: absorb, resist, recover from and more successfully adapt to seismic overloads (or over-displacements or over-energy in general) with respect to ultimate limit states required by design (Rousakis 2018). The critical columns may be redesigned to achieve higher horizontal displacement ductility while suppressing potential shear and steel detailing-related failures (in some cases) with additional external confinement (Anagnostou et al. 2019, Grammatikou et al. 2018a, b, He et al. 2015, Kalyoncuoglu et al. 2013, Bousias et al. 2007, Bournas and Triantafillou 2011, Anggawidjaja et al. 2006, Dai et al. 2012, Jirawattanasomkul et al. 2013, Biskinis and Fardis 2013, Seible et al. 1997 among else). Figure 3 gathers basic design or redesign philosophy for new or existing buildings respectively that results in maximum energy dissipation potential of suitably designed reinforced concrete frames. They utilize capacity design concept and prioritization of damage sequence as well as indirect (or direct in redesign) performance based design features (CEN EC8, GRECO 2017).

As mentioned in Rousakis (2018), alternative retrofit strategies at member or at structure level may include in general: increased strength or passive control or seismic isolation instead. Further, the sequence of desired damage accumulation at material and member level is discussed (Rousakis 2018) as well as the non desired failures that have to be suppressed especially in the case the retrofit strategy targets mainly high horizontal displacement ductility. It is important to remind that opposite to an elastic composite material confining means, steel confinement (internal or external) provides a weakened restrictive action after its yielding and up to its rupture thus accumulating damage. In that aspect it is not possible to act like damage barrier after its yielding.

### 2.1 Open Design Recommendation-Related Issues to Contribute to Member Resilience

Most guidelines for redesign of existing structures may neglect some aspects that need to be included, further clarified and thoroughly discussed so that designers may develop a strict Eurocode-conforming strategy. In that way the resilience of retrofits at member level may be further enhanced. At first, pre-dimensioning of the column as new one in order to check which requirements of the Eurocodes for new structures are not satisfied. This will better help designers to identify additional limitations that have to be also included in the redesign of the existing column with FRP strengthening but the design framework and the research done, needs further development (even for new structures), that is: identification of the most unfavorable loading combinations for different checks, incorporation of the knowledge levels during assessment and identification of unfavorable approaches for different materials (that is concrete might need different CFc and safety factors and not only one value, for different checks and especially for confinement – even not divided but multiplied), effects of second order moments and global instability checks before and after strengthening, effects of frame-by-frame approach in biaxial design for columns under axial load-biaxial moment and most unfavorable cases, shear design and most unfavorable biaxial shear-axial load cases, contribution of stirrups with inadequate anchorage or diameter or spacing, contribution of slender bars under compression given also inadequate stirrups that lead to buckling along more than two sequential stirrups or cases of columns with more than two slender bars in each column side or in lap-splice region, inadequate shear strengthening of existing large dimension columns without intermediate stirrup leg going through the section, predamaged columns (especially those with corroded bars or replaced concrete covers and effects on flexural strengthening with FRPs or checks on lap-splices), rocking behavior of columns, shear critical columns, the effects of the additional load, additional ductility or restricted ductility (in terms of concrete strain, section curvature or member displacement) because of the longitudinal bars etc. Further, the effects of environmental conditions and effects of all above on the reliability index required for the design and redesign by the Eurocodes depending on the time period considered should be discussed.

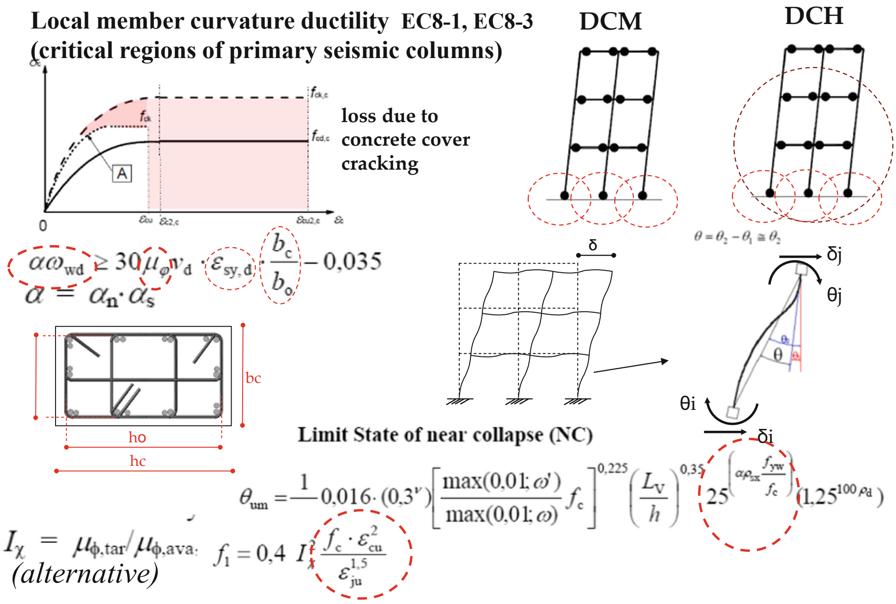



**Fig. 3.** Energy dissipation reserve of reinforced concrete frames through adequate confinement of concrete according to Eurocode 8 (EC8, GRECO 2017). Desired model for damage evolution and calculation of adequate confinement reinforcement in new and existing deficient columns.

Further, since local or global FRP strengthening through confinement aims at increased displacement ductility for the structure, there are cases the frames or buildings might have different q factors in different directions. Ductility due to overstrength should be also taken into account. The cases the buildings are excluded from the validity of inelastic pushover analyses approach should be clearly identified and similarly the cases that dynamic time-history inelastic analysis is required due to several global morphology or local detailing deficiencies. How are local detailing inefficiencies taken into account for such analyses?

Especially for concrete confinement, the conservative approach for increased global ductility to be consumed by the structure as “safe reserve” after ensuring “structure regularity” may not be straight-forwardly applied in existing structures due to above-mentioned deficiencies and therefore different approaches may be necessary as well as increased designers’ awareness. In that aspect lowering concrete strength after different redesign factors (safety, confidence etc.) might lead to unfavorable higher axial strain ductility (that is leading to unsafe limit states results).

Most generalizations of the existing well accepted design concepts in large structures are based on fundamental research and development on materials and most importantly on close–to-real-scale members through the crucial ‘design assisted by testing’ procedure to validate the insignificant (non detrimental) influence of yet-to-identify effects per specific application that make structural design an ‘art’.

Large scale dynamic experiments in small structures might help to demonstrate the whole procedure and identify bottlenecks all over the design process and provide straight-forward strategy to the designers to ensure redesign reliability index for already widely applied techniques such as externally bonded composites etc.

Further, the new retrofit techniques which utilize non bonded composite ropes, act like barriers of damage accumulation within the crucial confining means and succeed damage redistribution at material and member level. Since they lead to enormous axial strain ductility of concrete beyond practical demands, may help compensate for some of the above mentioned issues and thus achieve increased safety and resilience. In example, composite rope confinement of concrete (Rousakis 2014) may ensure practically unlimited axial strain ductility of concrete and thus compensate for the large errors in predicting the axial strain at failure of concrete with the existing design models (Fanaradelli et al. 2019) or of chord rotations (Anagnostou et al. 2019) in RC columns. Most importantly such practically unlimited axial strain ductility may be achieved also in deficient or repaired RC columns with very low section corner radius (Rousakis and Tourtouras 2014, Rousakis et al. 2019 etc.) as well as in cases we need to extend the adequate performance of the RC column beyond the fracture of existing external FRP confinement (hybrid in Rousakis 2013, Rousakis et al. 2019). Pretensioned composite rope confinement may additionally provide increased initial axial rigidity of the column and increased nonlinearity limit in order to withstand higher axial loads (Rousakis and Tourtouras 2014, Rousakis et al. 2019 etc.) while compensating for concrete creep.

However, as the construction practice is always ahead of design recommendations, to fully utilize the potential of all existing retrofits in a safe manner, advanced modeling may help identify and compensate for potential detrimental effects until all these aspects are suitably addressed in codes after validation by adequate testing. Suitable modeling framework is also of high significance for utilizing fully the Elastic Redistributable Uniform Confinement (ERUC) mechanism and concept.

# 3 Pseudo-dynamic FE Modeling Towards Advanced Structural Resilience

## 3.1 Strain Redistribution Effects in Rope Confinement

The novel design or redesign ERUC concept for collapse prevention and advanced resilience at system level may be further developed in a multidisciplinary and interdisciplinary manner in order to save human lives, critical infrastructure and social resources.

In order to cover different engineering systems and scales in a unified manner the following steps are necessary. At first, there is need to establish and develop necessary resilient oriented mathematical formulations at material, section, member and structure level and their interrelations to allow for advanced finite element (FE) analyses of complex structures. The experimentally observed effects of damage redistribution inside the concrete and in the FRP jacket due to external confinement action of flexible elastic composite rope (or fiber rope, FR) may be modeled with 3d finite elements and validated against existing experimental results. FR needs to be connected through friction with concrete or FRP (not fixed) enabling to redistribute stresses and strains and avoid local stress concentrations that lead to premature failure and to structural collapse and potential human casualties. It acts as damage barrier. FRP needs to be modeled suitably to reveal damage initiation and then according to interaction with concrete and FR to be fractured in multiple different positions. Concrete has to be modeled suitably to reveal extensive multiple cracking up to cohesion loss under the restrictive action of FR and even reproduce "spring-like" behavior during full unloading. Required mechanics of highly deformable materials and damage mechanics have to be utilized and further developed. FE analyses may provide the required unified framework to favor research of multidisciplinary and interdisciplinary developments of the novel design concept. The effects of the novel ERUC design concept have to be further explored at material micro-scale, at member and structure macro-scale to produce innovative and more resilient structures through hybridization and damage redistribution. Dynamic response of structures under seismic induced overloads has to be investigated. Most of the experiments concerning 3d structures in large facilities avoid testing up to collapse to avoid damaging expensive equipment or the facility itself. Further, this allows for retrofitting the structure and test again, given the high cost of such efforts. Similar approach is followed for retrofitted structures as well. Limited existing experiments of 3d structures loaded up to their detrimental collapse have to be fully utilized. Advanced 3dimensional FE analyses have to be extended beyond structural members to large complex structures under dynamic loads. In that way the effects of preloading, existing damages and sequence of construction of retrofit schemes when redesign of structure is concerned may be taken into account reliably.

In addition to several important studies towards or using 3dimensional FE modeling for concrete columns (Mirmiran and Zagers 2000, Rousakis et al. 2008, Karabinis et al. 2008, Lin and Teng 2017, Yu et al. 2010, Gambarelli et al. 2014, Jiang and Wu 2016, Jiang and Wu 2012, Piscesa et al. 2018, Mohammandi et al. 2019 among else), the pilot study by Fanaradelli et al. (2018) provides a suitable pseudo-dynamic inelastic 3-dimensional FE analysis of composite rope confined concrete reproducing most of the abovementioned effects. Most importantly, it allows for the strain redistribution of the elastic confinement provided by the composite rope throughout loading. Therefore, it could be considered an analytical mechanical analogue to explore the potential of the ERUC design concept. Figure 4 illustrates the strain redistribution between the confining means and the concrete core during the analysis of specimen VinL1v1R1 tested in Rousakis (2014). The rope at different levels of the column axis shows variable stress and strain during the analysis (Fig. 4). Different analyses snapshots of the half of the column and of the corresponding rope, clearly depict the variable deformation and tensile stress of the non bonded rope throughout the axial loading (imposed deformations) of the column up to the ultimate. The first snapshot, before loading, shows the spiral rope before being stretched due to concrete dilatation. The rope is deformed and slipping around the concrete column to meet the variable dilatation demands.

The axial stress-axial strain response of the concrete column shows marginal temporary load drop similar to the experiments and ultimate stress and strain values close to the experimental ones (Fanaradelli et al. 2018). The analytical stress – strain curve for specimens of VinL1v1 group subjected to axial compression is depicted in Fig. 2. The FE analysis may capture satisfactorily the general stress – strain behavior of the column, the temporarily load stabilization after extensive concrete cracking and the subsequent load increase up to very high axial strains.

It is validated that suitable FE modeling can provide the mathematical basis for reliable representation of geometrical and material nonlinearity or non-linear interaction between materials in their contact points or surfaces or slippage (non bonded materials) etc. Reliable FE modeling required consideration of suitable models for the concrete and the composite rope and for their interactions. The advanced nonlinear 3 dimensional analytical FE models were developed and analysed with Ansys Workbench R15, EXPLICIT DYNAMICS (ANSYS 15.0) finite element software. Concrete was modeled with eight-node solid element utilizing the RHT advanced plasticity concrete model for brittle materials (Riedel et al. 2009) and suitable for dynamic analyses. The RHT constitutive model is a combined plasticity and shear damage model in which the deviatoric stress in the material is limited by a generalized failure surface of the form:

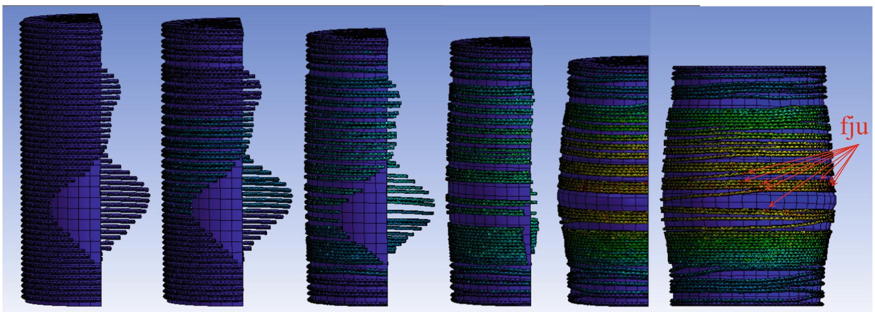



**Fig. 4.** Snapshots of the half concrete cylinder and of the confining composite rope during successive analysis steps and up to ultimate to illustrate relative concrete-rope displacements. Last snapshot shows near maximum rope tensile stress fju (red color) at different rope elements.

$$f\left(P, \sigma_{eq}, \theta, \dot{\varepsilon}\right) = \sigma_{eq} - Y_{TXC(P)} * F_{CAP(P)} * R_{3(\theta)} * (F)_{RATE(\dot{\varepsilon})} \tag{1}$$

sensitive in pressure hardening, strain hardening, strain rate hardening, third invariant of deviatoric stress, shear induced damage and coupling of damage due to porous collapse.

The composite rope was modeled as an equivalent hexahendral solid element with "frictionless" interaction with the concrete core. In this study, a pseudo-dynamic imposed axial deformation history on the concrete column was performed.

### 3.2 Seismic Retrofitting of RC Columns with FRPs

Similarly, efficient seismic strengthening of very demanding RC columns (or joints etc.) with advanced materials and novel techniques may be significantly upgraded with the use of dynamic nonlinear 3d FE analysis. The study by Rousakis et al. (2018) presents the pilot pseudo-dynamic analytical results for column L0S_R2, tested under combination of axial load and imposed cyclic horizontal displacements by Bournas & Triantafillou (2009, 2011). Concrete was modeled with RHT as already presented while the steel reinforcement was modeled using a two-node Beam (Line) element (Fig. 5d) considering a material that yields and hardens. The plastic deformation was computed by reference to the Von Mises yield criterion. The condition is:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\Upsilon^2 \tag{2}$$

The yield surface is extended uniformly with Multilinear Isotropic Hardening. The CFRP sheets were modelled as Hexahedral and Tetrahedral solid 8-node elements. The interaction surface between CFRP and concrete was considered bonded as the jacket was externally bonded with epoxy resin. The response of the CFRP material was considered orthotropically elastic while stress limits, strain limits and failure criteria (Tsai Wu) were defined.

The columns had section side of 250 mm and 1600 mm height (half column, Fig. 5). The specimens were subjected to constant axial compressive load (28% $N_{Rd,crush}$) and then to lateral deformation. Similarly, in FE analysis the same axial load was imposed and then a horizontal displacement history on the top of the column, pseudo-dynamically. Figure 5a shows satisfactory convergence of the finite element analysis results (blue curve) against the experimental (black curve) horizontal load-normalized displacement % (drift) for the constructed model of Fig. 5d.

standalone frames with 3-dimensional

The column presented extensive concrete cracking and bar yielding inside the FRP jacketed column length. In addition, damage accumulation through concrete cracking and bar buckling extended beyond the FRP confined area (Fig. 5b) while there was local fracture of the FRP jacket at the bottom area (Fig. 5c). The FE analysis shows similar damages in Figs. 5e and 5f.

Three-dimensional dynamic FE modeling may help identify additional design parameters and enable for further optimized retrofits and enhanced resilience and safety of members.

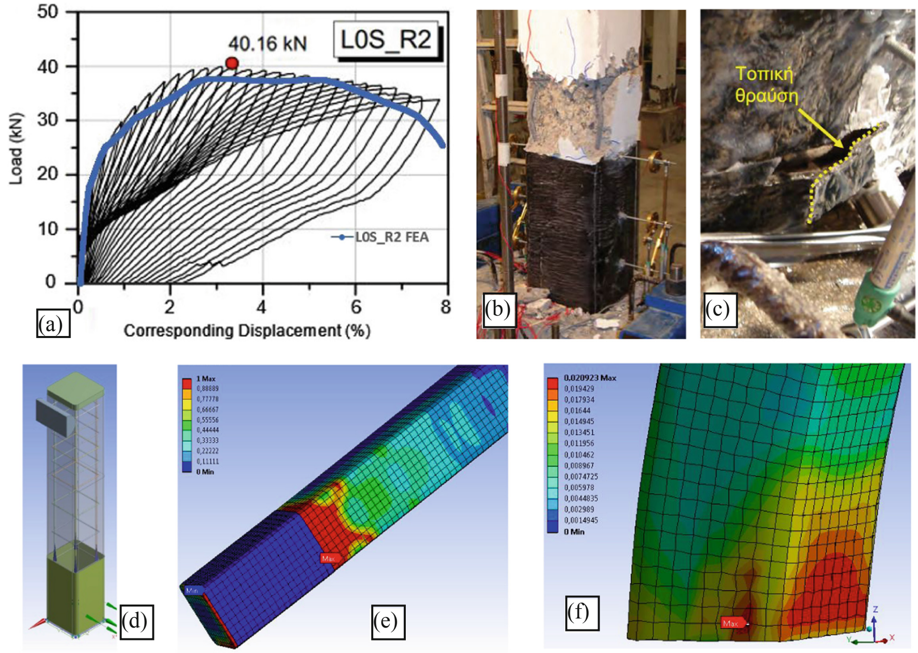
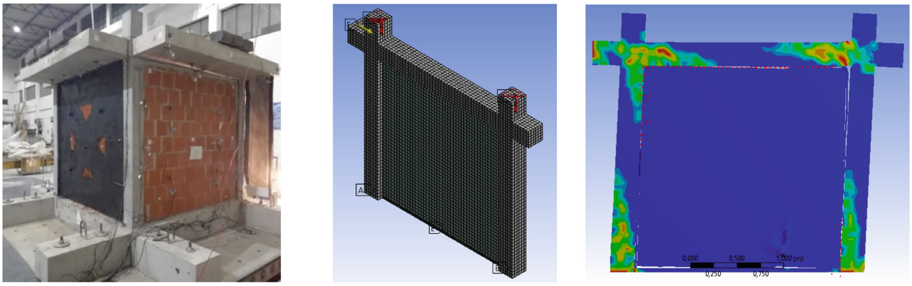



**Fig. 5.** Three-dimensional pseudo-dynamic finite element analysis results of the model depicted in (d) against the experimental results for specimen L0S_R2 (from the experimental study by Bournas and Triantafillou 2009). Comparison of the horizontal load versus top displacement (a). Characteristic damages extended over the jacketed region as observed in the experiments (b, adapted from Bournas & Triantafillou) and in the analysis (e) using the damage criterion (1 corresponds to fully damaged concrete). Local fracture of the CFRP jacket during the experiments (c, adapted from Bournas & Triantafillou) captured with the analysis (f).

## 4 Dynamic 3-Dimensional Finite Element Modeling for Seismic Table Experiments of Resilient Interventions of Brick Infilled Reinforced Concrete Framed Structure

Early studies by Rousakis et al. (2017) and Rouka et al. (2017) have investigated the effects of the strengthening of the brick infills with composites bonded externally with highly deformable polymers. Such strengthening in masonry walls has been proven very efficient in transforming the masonry walls into sufficiently ductile structural members (Gams et al. 2014). Parametric studies have shown that suitably designed selective infill strengthening may utilize higher initial stiffness and base shear of the structure because of the engagement of the infills while maintaining sufficient residual base shear after damage accumulation within the ductile infills. Recent experiments (Akyieldiz et al. 2020 and Rousakis et al. (2020a, b) have validated the in-plane and out of plane satisfactory performance of orthoblock infills protected with highly deformable polymer joints at the RC frame – brick infill interface or repaired with fiber grids bonded with highly deformable polymer joints. The latter experiments concern shake table tests of real scale RC structure (Fig. 6a adapted from Rousakis et al. 2020b). In that case it is very demanding but promising the pilot analysis of standalone frames with 3-dimensional FE (Fig. 6b and 6c adapted from Rousakis (2021a, b)).



(a) (b) (c)

**Fig. 6.** Shake table tests within INMASPOL project SERA-TA framework (a). Three-dimensional pseudo-dynamic finite element model (b) and pilot analysis (c) of infilled frame with polymer joint.

## 5 Conclusions

Advanced retrofit materials and innovative techniques may be utilized in increasing the resilience and safety of critical RC buildings and infrastructure. Several open issues in redesign of deficient existing RC structures require special attention to achieve the desirable reliability index. Some of them are relevant to special retrofit detailing or existing deficiencies that urge for further development of the existing design guidelines. In particular, seismic resistant redesign may require in some cases dynamic approaches. Advanced dynamic 3-dimensional finite element modelling may provide the necessary multidisciplinary and interdisciplinary analytical framework towards holistic assessment of structural materials, members and structures to rigorously bridge that gap and help fulfil urgent needs in construction practice. Such analytical framework may be continuously updated throughout the structure life-time, towards a more reliable estimation of safety and resilience of critical buildings and infrastructure while minimizing the necessary experimental validation. Furthermore, this sound analytical basis may help integrate new hybrid techniques and new concepts (such as Elastic Redistributable Uniform Confinement, ERUC concept) to further increase structural safety and resilience.

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