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Inherent seismic resilience of RC columns externally confined with nonbonded composite ropes

Theodoros C. Rousakis

Laboratory of Reinforced Concrete, Department of Civil Engineering, Democritus University of Thrace (DUTh), Vas. Sofias 12, Xanthi 67100, Greece

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ABSTRACT

This paper highlights the inherent seismic resilience of reinforced concrete (RC) columns externally confined with nonbonded composite ropes. It critically reviews the inherent seismic resilience reserve of such columns at material, at section and at member level. The study further elaborates recent experimental evidence to reveal the structural resilience of the retrofit technique (excluding risk-based assessment). It focuses on the damage build-up and control at member level that may prevent the collapse of critical infrastructure. A new generalized design concept is concluded towards enhanced inherent resilience of similar members. It applies to members with the weakest link (in this case also being the main bearing material, the concrete core) suffering a local damage, susceptible to further build-up. This damage localization disrupts uniformity and homogeneity in response. The design approach suggests that adequate confining action with continuous elastic flexible rope (or tape) may preserve damage-sensitive-restriction in a way that globalizes damage. It may succeed damage redistribution inside the core throughout loading and make the core again more uniform and more homogeneous in response, thus maximizing energy dissipation.

1. Introduction

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” [18]. It covers different fields such as ecology [13], materials science and disaster mitigation in communities. Resilience of built environment [2,3,5–7] is important to community and there is need to improved performance during and after a disruptive hazard event [17]. Improved metrics should account for resilience of the components, infrastructure systems and whole communities. The current study focuses on earthquake induced hazard and on inherent resilience reserve of reinforced concrete (RC) columns as critical components of structures.

Assessment of seismic resilience of concrete structures utilizes advanced risk-based probabilistic analytical approaches [2,3,5–7]. Recently, Biondini et al. [1] included in their investigation the additive effects of chloride-induced corrosion of steel reinforcements in existing concrete structures. They concluded that time-dependent effects of corrosion may reduce functionality and resilience during a seismic event. Functionality of the structure is associated with its seismic capacity. Their research indicates the importance of including in the seismic design of resilient structures all potential hazards for the whole life-cycle. This approach results in similar requirements for efficient retrofit of RC structures. In another study, Echevarria et al. [10] highlighted the improved resilience of critical bridge infrastructure when concrete-filled fiber reinforced polymer (FRP) tube (CFFT) columns are used, instead of RC ones. They performed a comprehensive experimental study of columns suffering blast, fire or earthquake hazards (multi-hazard experimental assessment) of different intensity. They concluded lower damage of the columns, lower restoration time and lower repair costs for the case of CFFT. Of course, multilevel societal needs and societal potential, need to be satisfied through the development of risk-based performance goals [4,17]. Bocchini et al. [4] proposed an advanced risk assessment approach to unify resilience and sustainability requirements. More recently, Dong and Frangopol [9] examined the resilience of highway bridges subjected to mainshock and aftershocks. They assumed that uncertainties of several aspects increase in the cases of aftershocks and should take aftershocks into account to assess bridge seismic performance. Thus, new challenges arise about resilient seismic retrofit design and use of advanced materials instead or beside steel reinforced concrete. They also concern their time-dependent durability and the effects of multiple earthquake induced shocks, within the framework of whole life-cycle assessment. Alternative solutions in design of new structures or in seismic redesign of existing ones may affect greatly the resilience of infrastructure and of the community as whole.

The current study highlights for the first time, the inherent structural resilience of RC columns of existing structures retrofitted with

E-mail address: trousak@civil.duth.gr.

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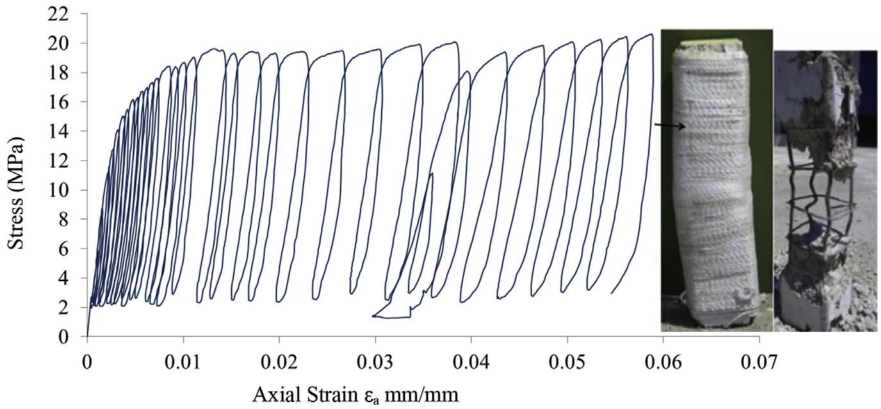

Fig. 1. RC column 500PPL4 wrapped with composite rope passive confinement. The high deformability composite rope maintains full contact with variably deformed concrete core and internal steel cage and maintains full axial load capacity. When the rope is removed, the concrete core is revealed totally and uniformly cracked.

composites ropes, under seismic excitations. The investigation focuses on the performance of the columns to preserve their axial capacity. Echevarria et al. [10] recognize the significance of this issue as in example, after an earthquake a bridge may be still in service to provide first responders and emergency vehicles access to exclusive regions affected. Similarly, RC critical infrastructure (hospitals, fire stations and command centers, etc) may require similar performance levels as a whole to operate efficiently. The current study considers the retrofitted RC column a resilient subsystem, being critical component of structure that belongs to a network of critical infrastructure to fulfill resilience requirements. Further, the investigation critically reviews resilience of materials and of sections within the subsystem and concludes a general design concept towards enhanced resilience of columns. Resilience of post-earthquake damaged columns is briefly discussed as well.

2. Structural inherent resilience

This study contributes to the resilience-related framework for retrofitted RC columns. In that case, the resilience may be interpreted as the ability of the retrofitted RC columns 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. This study considers mainly columns redesigned to overcome above challenges with increased displacement ductility, through externally confined concrete. Adequately confined concrete succeeds desirable axial strain ductility to satisfy the required ductility at section and at member level. Alternative retrofit strategies at member or at structure level may include in general: increased strength or passive control or seismic isolation of the structure instead. Residual axial load capacity at high displacement ductility requires suppressing fragile-type failures to ensure steel bar yielding and hardening, up to emergence of global instability. Such failures include concrete shear failure, concrete core compressive failure and steel bar premature buckling under compression. They also involve relative slip of steel bars at lap splices, anchorage failure of steel stirrups or premature fracture of FRP confinement jacket. Therefore, redesign of RC members aims at prevention of abrupt, fragile cracking of concrete leading to significant load bearing capacity loss. Failure of resistance mechanism in general is also important to prevent, to achieve increased displacement ductility. Yielding of steel bars and adequate confinement of concrete, are the two basic mechanisms at member level to dissipate earthquake-induced over-energy in general. In cases that confinement involves steel stirrups, yielding of steel results in the existence and build-up of residual (plastic) strains and in lower post-yielding tensile modulus. Therefore, the restrictive action of steel weakens. For further loading, the damage build-up in that specific area reveals higher rate and may lead to member failure as the concrete core disintegrates.

2.1. Composite rope confinement effects on structural resilience of RC columns

Non-bonded, non-resin-impregnated composite rope wrapping of columns may succeed in the above tasks. Adequate composite rope wrapping may ensure maximum use of concrete axial strain potential, as it allows for lateral strain redistribution according to varying demands of the column. These varying demands depend on the concrete cover dimension, strength and cracking, and on the confined concrete core response (lateral dilation). They also depend on the steel stirrup yielding initiation and hardening plateau, on the bar buckling sensitivity and on the section shape and reinforcement detailing within the section. All abovementioned parameters have varying effects throughout random and time-dependent axial and lateral loading of columns during earthquake excitations and may restrict the displacement ductility at member level through local damage build-up. However, the potential for redistribution of lateral strain in the case of composite rope wrapping causes redistributed damage and thus extensive and uniform cracking of concrete [20–22,24] for monotonic or cyclic compressive load. This unique characteristic at section level may contribute to improved seismic resilience of the column being under varying axial loads. Fig. 1, shows RC column 500PPL4 with square section from Rousakis and Tourtouras [24], wrapped with polypropylene fiber rope (PPFR). The column displays global buckling, multiple local bar buckling, multiple local bulging of the concrete core and intact composite rope, while preserving the axial load bearing capacity (see Fig. 1). This test was early stopped as depicted in Fig. 1, carrying ever-increasing axial load at 0.06 concrete axial strain. Therefore, the reserve of inherent structural resilience of the concrete core against axial loads – if assessed in terms of axial strain ductility - and of the column as whole, is even higher. Lateral strain redistribution capacity of flexible non-bonded elastic material enables for optimum damage redistribution at material level. That is, concrete core bulges over multiple regions along the column axis and different steel bars present multiple buckling respectively. This confinement restricts damage extremes in regions of first damage build-up as it mobilizes remaining non-damaged areas through redistribution and consequently utilizes greater percentage of materials existing in the column. Similar is the behavior of the same column being repaired after its original loading with high strength non-shrinking mortar, 6 layers of non-bonded, non-resin-impregnated basalt fiber tape and 4 layers of PPFR (column RCrepBFTL9PPL4R in Ref. [30]). The column was subjected to identical cyclic axial loading with 500PPL4 and revealed heavy cracking of the concrete core with large non-uniformities due to local replacement of pre-damaged core and cover regions with high strength mortar. Steel bar buckled at different regions. The hybrid basalt-polypropylene wrapping revealed remarkable insensitivity to local damage build-up and kept the heavily cracked concretes of different strength and buckled bars in place [30]. The stress-strain curve of

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