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A strategy for the finite element modeling of FRP-confined concrete columns subjected to preload

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ABSTRACT

Compressive behavior of columns strengthened by means of an outer elastic confinement provided e.g. by fiber-reinforced polymer (FRP) jackets has become a main topic in the field of structural retrofitting. In details, the problem of the response assessment of strengthened columns is still under study. Many analytical formulations have been proposed to describe the compressive behavior of confined concrete under both monotonic and cyclic loads. However, the effect of a stress/strain level in the columns already present prior to apply the confinement has been generally neglected until now, also because of the lack of well defined strategies of modeling.

In this frame, here, (1) a FEM assessment strategy is presented and discussed referred to FRP-confined reinforced concrete columns subjected to monotonic compressive loads; (2) to this aim, first, a modified stress-strain law for the concrete is proposed for the FE analysis able to capture the softening/hardening behaviour differently from the laws of unconfined concrete commonly used as input; (3) then a law to fix the parameters defining the hardening/softening characteristics starting from the characteristics of the unconfined concrete and of the FRP wrapping is provided.

After calibrating and validating the above strategy in the case of non preloaded elements, the compressive behavior in the presence of preload is analyzed numerically and compared with experimental results to evaluate the reliability of the FE model approach proposed. Through the paper, the procedure for the definition of the law to fix the hardening/softening parameters of the concrete is described.

1. Introduction

The assessment of confinement effects provided by FRP jackets is an important structural engineering topic. In the practical applications, FRP wraps are applied to structural members (mainly columns) that require an increase of bearing and/or deformational capacity. As it is well known, it is not always possible to unload the columns before applying the FRP sheets. On the contrary, the intervention is often carried out under service load conditions (as in the case of bridge or buildings).

In the last decades, several authors have addressed the evaluation of the capacity of reinforced columns under unstressed/undeformed conditions at the time of application of the FRP wraps. However, very few resources are available regarding the capacity of columns reinforced while loaded (i.e. in a preloading state). The consequence is that how an existing stress/strain at the time of the intervention could change the performance of reinforced members is still unclear. This lack of knowledge is due to the difficulty of performing realistic tests therefore numerical-analytical approaches fail being frequently not calibrated in a satisfactory way.

Only few studies can be found in the literature not always leading to the same conclusions. Pan et al. [1] presented an experimental investigation on square concrete columns reinforced with carbon-fiber-reinforced polymer (CFRP) sheets subjected to compressive loads after a preloading of the specimens. The authors observed that if the preloading increases the axial capacity reduces.

He et al. (2009) [2] investigated the expansion ratio of circular columns strengthened with CFRP sheets under preloading and observed that increasing preloading, in the mid-low range, produces a decrease of the expansion ratio, whereas this effect reverses for increasing levels of preloading in the mid-high range. This fact changes the ductility of columns. Shi and He (2009) [3], by utilizing the software Abaqus, conducted numerical simulations on cylinders confined with CFRP sheets under different preload levels and observed that, by improving the stiffness/thickness of the fibers, the short-term preloading effects can be neglected. Later, He and Shi (2009) [4], used the same

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numerical modeling technique to investigate the static lateral responses of CFRP-confined concrete columns loaded at the time of the reinforcement application. The authors concluded that the effect of sustained loads on the static lateral response of such columns are negligible if time-dependent effects are excluded. An experimental study carried out by He and Jin (2011) [5] on cylinders under different preloading levels shows that the effects of preloading can be neglected if the columns are strongly confined. Li et al. (2011) [6] proposed an analytical model to evaluate the constitutive law in compression of preloaded square concrete columns confined with CFRP. Morsy et al. (2012) [7] presented an experimental investigation on the behavior of axially preloaded short circular columns repaired with carbon-fiber reinforced polymer. The test results indicated that a preloading stress may yield a slight positive effect on the capacity of confined columns.

A recent study presented by Pan et al. (2015) [8] shows an analytical approach for the evaluation of the axial strength and strain capacity of circular and square columns confined with CFRP sheets, based on experimental observations documented in previous studies.

Based on the above literature, it is evident that there are too many points of view and different opinions on this topic and it is unclear if preloading effects could be considered positive or not. Additional investigations and reliable response prediction models seem to be necessary to fill this gap and to provide a better understanding of the confinement action. In this frame, here a strategy for the FE modeling is provided. In details, the implementation of a finite element approach for the assessment of the effects of preload on the FRP confinement is discussed. In the Abaqus environment, an appropriate modification of the default parameters of the Concrete Damaged Plasticity Model (CDPM) is proposed. Further a fictitious stress-strain law for the concrete is presented, able to capture the overall behavior of a FRP wrapped R.C. column with special attention to the hardening/softening behavior. Further, analytical functions for fixing the parameters of the concrete fictitious stress-strain law starting from the mechanical characteristics of the unconfined concrete are obtained for the practical applications. The results of the analyses are compared with the results obtained from recent experimental researches for an evaluation of the reliability of the proposed procedure.

2. FEM modeling

2.1. Element type and meshing

The numerical simulations concentrate on concrete cylinders with different aspect ratios and different concrete strength wrapped with different types of FRP to observe the compressive response of the confined concrete in a wide range of mechanical confinement ratios. The concrete cylinder was modeled with C3D8R elements (8-node linear brick, reduced integration, hourglass control) while the FRP sheet was modeled utilizing S4R elements (a 4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains).

Tie constraints define the nodal interaction between shell and cylinder. In agreement with several previous studies (e.g. Issa et al. (2009) [9], Yu et al. (2010) [10], Yu et al. (2011) [11], Taghia et al. (2016) [12], Hany et al. (2016) [13]), the assumption that no sliding occurs during the loading process seems to be reasonable. In order to validate this assumption, some initial parameter studies were performed by the authors defining both "cohesive interaction" and "tie constraints interaction" between the contact surfaces. It was observed that the differences of the results are negligible. Moreover, it was detected that, by assuming "tie constraints interaction", the computational efforts are reduced.

2.2. Boundary conditions

As it is well known, changing boundary conditions can modify the response of a model. Particular attention should be paid during finite element modeling for the definition of the end constraints. Several authors investigated the effect of end constraints and the system's response by changing the respective constraining conditions. As shown in Teng et al. (2015) [14], in the case of no end constraints both the axial strains and the compressive stresses are uniform and in line with the symmetry of the system. When the constraints are added to the model, stresses and strains become non-uniform and the system response is characterized by a lower capacity due to a non-uniform confinement.

However, the influences of system geometry and aspect ratio have to be considered in the definition of the boundary conditions. Other previous studies (e.g. Yu et al. (2010) [10], Yu et al. (2011) [11], Hany et al. (2016) [13]) showed that for cylinders having a height twice the diameter, the configuration of the end constraints does not significantly influence the response of the system. Moreover, it is also possible to only model a slice rather than the full-scale specimen, thus decisively reducing the computational effort.

In the present work, boundary conditions were defined assigning displacements and encastres to the reference points of rigid bodies at the top and the bottom of the model respectively.

2.3. Materials properties

2.3.1. FRP sheets

Elastic properties of the FRP sheets can be specified in Abaqus by "Lamina" material type, which allows correlating the longitudinal and transverse elastic moduli $E_{1,}$ E_2, the rigidity moduli G_{12}, G_{13}, $G_{23,}$ and the Poisson coefficient N_{u12}. In the case of unidirectional fibers, it is possible to specify only E_1 and to assign very small values to the other elastic parameters so that the system is not affected by an interaction with the other directions.

2.3.2. Concrete

Modeling of concrete for the evaluation of confinement effects provided by FRP wrapping is one of the most sensitive stages of the FEM definition process and is in direct relation to the accuracy of the results. There are two different models allowing to define concrete behavior with the Abaqus software: Drucker-Prager D-P type plasticity model and Concrete Damaged Plasticity Model (CDPM). In the last decades, several studies have been carried out to investigate the influence of the definition of the material parameters. Many authors found out that by taking the "default values" for the concrete in both models (D-P model and CDP model), not realistic results are achieved in comparison with the behavior observed in experimental investigations. Different formulations for the calibration of the parameters to be used for the concrete properties in the case of FRP confinement were proposed in order to obtain a good agreement with experimental data. Although several studies can be found using the Drucker-Prager type plasticity model (exemplarily refer to Yu et al. (2010) [10], Wu and Jang (2012) [15], Youssf et al. (2014) [16], Karabins et al. (2008) [17], Jang and Wu (2014) [18]), very few resources are available in the literature utilizing the Concrete Damaged Plasticity Model (Yu et al. (2010) [11], Hany et al. (2016) [13], Ozbakkaloglu et al. (2016) [19], Kabir and Shafei (2012) [20], Michal and Andrzej (2015) [21], Papanikolau and Kappos (2007) [22] represent all references available to date). In the present paper CDPM is suggested for the modeling of confined concrete. Concrete Damaged Plasticity Model allows reproducing the behavior of concrete by defining the plasticity and/or the damage parameters. In the Abaqus environment it is possible to take into account concrete cracking in tension as well as crushing in compression. The behavior of concrete under multi-axial stress state is defined basing on the *damage variable*, the *yield criterion*, the *flow rule* and the *hardening/softening* rule. The *yield criterion* described in Lubliner et al. (1989) [23] and modified in Lee and Fenves (1998) [24] sets out the yielding conditions when concrete is under multi-axial compression, while the *flow rule* determines the direction of the plastic deformations and describes the