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Dynamic analysis of walls strengthened with composite materials

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ABSTRACT

The bidirectional dynamic behavior of walls strengthened with composite materials is studied. For that purpose, a multi-layered high order finite element is developed. The finite element accounts for the bidirectional (plate-type) dynamic behavior and for the interfacial interaction between the adhesively bonded components. The formulation uses a viscoelastic first order shear deformation orthotropic plate theory for the independent modeling of the existing wall and the composite layers and a high order theory for the displacement fields of the adhesive layers. The Finite element framework simplifies the coupling with adjacent structural elements and the use of standard computational procedures. The convergence of the formulation and two numerical examples are studied. The first case studies the response of a strengthened wall to a step base acceleration. The second case studies a wall built in a surrounding frame and strengthened on the outer face. The numerical study examines the capabilities of the model and reveals some of the unique aspect of the dynamic response, including the effects of the orthotropy and orientation of the strengthening system. It also highlights the potential of the high order finite element to become a platform for the modeling and dynamic analysis of the strengthened wall.

1. Introduction

The deterioration of aging structures and the increased awareness of dynamic, seismic, and wind loads trigger the need for structural strengthening. In many cases, the strengthening effort draws the attention to the dynamic upgrade of walls. One strengthening technique that has gained popularity over the past two decades uses externally bonded composite materials and fiber reinforced polymers (FRPs). In the case of strengthening of walls, the objective of the strengthening procedure is to improve the flexural and the in-plane shear resistance of the wall. While the out-of-plane strengthening contributes to the safety of the wall itself, the in-plane strengthening can contribute to lateral load resistance of the entire structure. In that sense, it can contribute to the dynamic or seismic upgrade of the structure.

Naturally, most of the attention in the field of strengthening of walls with composite materials has been drawn to the upgrade of masonry structures. Correspondingly, the majority of the literature in the field and the documentation of experimental results (including the ones that will be surveyed latter in this section) focus on FRP strengthened masonry walls. Nevertheless, many of the physical phenomena that govern the response of the composite structure, and particularly the ones associated with 3-dimensional (3D) dynamic stress and deformations fields, are general and they apply to masonry as well as monolithic (orthotropic or isotropic) strengthened walls. It is therefore emphasized that as a first step in addressing the dynamic response of strengthened walls in general, the present paper tackles the case of FRP strengthened monolithic walls.

The dynamic behavior of any monolithic or masonry wall strengthened with externally bonded composite layers is governed by a variety of 3D physical phenomena. In many cases, the 3D dynamic response is also affected by the coupling between in-plane and out-of-plane responses. Such coupling evolves due to loads that are not parallel or perpendicular to the wall's plane, due to asymmetric application of the FRP system on one side of the wall, or due to inter-story drift. Eccentricity of the wall with respect to the supporting frame (see, for example, Almusallam and Al-salloum [1]) and the interaction with surrounding structural elements may also contribute to the evolution of a 3D dynamic response. The experimental studies reported in Valluzzi et al. [2], Al-Chaar and Hasan [3] and Turek et al. [4] well demonstrate these 3D effects and their impact on the response of the wall.

Another major contributor to the unique 3D dynamic response is the bidirectional out-of-plane (two-way flexure) and in-plane (membrane) behavior. In certain cases, out-of-plane loading may yield a unidirectional response (see, for example, Hamed and Rabinovitch [5,6]) but, in general, the integration of the FRP strengthened wall in the dynamic retrofit system yields a bidirectional response. In particular, the in-plane shear loading yields bidirectional response and evolution of compressed and tensed diagonals. The direction of these diagonals, as well as the cracking of the wall and the buckling of the FRP layer they may trigger (El-Dakhakhni et al. [7], Altin et al. [8], Rabinovitch [9]) change during the dynamic response.

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The potential orthotropy of the existing wall and that of the externally bonded layer is also a major contributor to the complexity of the 3D dynamic response. Orthotropy of the existing wall may be due to the nature of the building material or due to the building technique. Orthotropy of the FRP system may result from the orientation of the fibers in the composite layers. In both cases, the orthotropy affects the bidirectional behavior of the wall (see, for example, Ehsani et al. [10]) and it may yield a complex 3D dynamic response.

Finally, the interaction between the existing and the supplemental layer plays a critical role in the dynamic response of the composite structure. This interaction is achieved by means of shear and out-of-plane normal (peeling) stresses in the adhesive layer and mainly at its interfaces. These stresses, and their tendency to concentrate near irregular points, may eventually lead to accumulation of interfacial damage or delamination. The latter effect, as well as the tendency of the cyclic or sign reversing loads to increase the size of the delaminated area, were observed in the experiments reported by ElGawady et al. [11,12], Stratford et al. [13] and Yuksel et al. [14]. It is also reflected by analytical and numerical studies, see for example, Milani [15,16], Milani et al. [17,18], Rabinovitch [9].

The above observations indicate that the dynamic response of the FRP strengthened wall (either monolithic or masonry) is 3D by nature. Furthermore, it involves global, localized, and interfacial effects, which are all critically affected by the 3D nature of the problem. As such, it defines significant analytical and computational challenges that have to be faced by the dynamic analysis of the strengthened wall.

One of the approaches that aims to face the above challenge focuses on the global in-plane behavior and adopts a strut model (Haroun and Ghoneam [19], Jai et al. [20,21], Binici and Ozcebe [22], Binici et al. [23] and Marcari et al. [24]). In this approach, the wall is modeled as a compressed diagonal strut and the FRP system is modeled as a tensioned bar, both installed in a planar frame. This family of models can capture some aspects of the global response but it cannot model the coupled in-plane and out-of-plane behavior or the interaction between the existing and the supplemental layers through the bonding mechanism.

A more refined class of models focuses more on the local scale but makes a distinction between the in-plane and the out-of-plane responses. In many cases, the strengthened wall is considered as a unidirectional (one way) flexural member (Triantafillou [25], Kiss et al. [26], Hamed and Rabinovitch [27–29]). This type of modeling does not address the effects associated with the bidirectional out-of-plane behavior and the in-plane response to shear loads. For example, Hamed and Rabinovitch [29] presents a geometrically and physically nonlinear model of a unidirectional strip taken out of a strengthened wall. This model does not take the 3D bidirectional response into account and therefore it is only suitable for cases where such action does not take place.

A different modeling approach focuses on a 2D response and adopts analytical solutions (Elgawady et al. [30]) or, mostly, standard 2D finite element (FE) models (Meftah et al. [31], Arulselvan et al. [32], Luciano and Sacco [33], and Lourenço et al. [34]). In cases involved with masonry walls, homogenization procedures are commonly used for the definition of equivalent properties to be used in the finite element analysis (e.g. Luciano and Sacco [33], Cecchi et al. [35] for FRP strengthened masonry walls, Milani [15] for walls strengthened with FRP grids, and Cecchi et al. [36], Mistler et al. [37] and Lourenço et al. [34] for unstrengthened masonry walls). Extension of the homogenization approach to the 3D domain is also reported (e.g. Milani [38]). While the homogenization procedures span between the unique masonry characteristics and the FE platform, they limit the ability to represent the localized phenomena and mainly the 3D ones that couple the dynamic in-plane, out-of-plane, and interfacial effects. In other cases, capturing these phenomena require significant computational efforts. Thus, in spite of its advantages, the application of the FE method in its standard 2D form to the dynamic analysis of in-plane loaded FRP strengthened walls is involved with several limitations. In particular, the severe computational difficulties due to the differences in geometrical and mechanical scales and the indirect consideration of the out-of-plane peeling stresses in the planar analysis (Grande et al. [39]), limit the effectiveness on this type of analysis.

The most refined approach aiming at the dynamic analysis of the strengthened wall uses 3D FE analyses. In this case, the demand for 3D meshing, the localized effects, the interaction between the existing and the bonded layers through a 3D stress and displacement fields, the coupling effects, the differences in length scales and elastic properties, and the presence of irregular points end up with a large computational problem. For example, Davidson et al. [40] used over 100,000 3D solid elements to model a narrow strip of strengthened masonry wall under a unidirectional type of response to blast loads. Interpolating this number to typical walls under coupled in-plane and out-of-plane bidirectional dynamic action may end up with millions of degrees of freedom.

Another critical aspect of the structural response of the FRP strengthened wall and the interaction between the existing and the supplemental layers is the evolution of delaminations and debonding failures [11–14]. Numerical models for the delamination of the FRP from the substrate are presented in Milani [16], and Milani et al. [17]. In these models, the delamination and its brittle nature are considered within the framework of a limit analysis of the FRP strengthened wall through a brittle yield surface of an interface with a negligible thickness. The unified model provides an upper-bound/lower-bound estimation of the collapse load. In Milani [38] the limit analysis concept is augmented to multi-layered historic masonry walls. Milani [15] uses two approaches for the consideration of delaminations of FRP grids from a masonry wall. The first one considers the FRP grid as truss elements and limits their tensile strength due to possible delamination. The second one uses plate elements for the modeling of the FRP reinforcement and uses an interfacial law for the simulation of delaminations. In Fedele and Milani [18], the 3D effects in the debonding mechanism are studied by introducing a quasi-brittle response of the adherends through an elastic-damageable model. Other approaches for the consideration of delaminations range from energy balance methods (e.g. Au and Buyukozturk [41], Achinta and Burgoyne[42]), virtual crack closure methods (e.g. Greco et al. [43]) or cohesive interface approaches (e.g. Rabinovitch [44,9]).

The critical role that the delamination failure mechanism plays in the structural behavior of the FRP strengthened wall draws the attention to interfacial effects that trigger and govern this failure mechanism. The tendency of the debonding to nucleates near localized irregularities, the 3D effects involved, and the potential impact of the process further stress the importance of the interfacial stresses. As these interfacial stresses stem from the 3D stress fields in the adhesive layer, it highlights the challenge associated with their assessment.

The above literature survey reveals that the challenges associated with the structural response of the FRP strengthened walls require a special modeling and analysis approach. In particular, the 3D coupling due to loading, inter-story drift, asymmetric strengthening, and interaction with adjacent elements, the interaction between the existing and the bonded layers, the 3D effects, the bidirectional flexure, and the dynamic response set a major analytical challenge. These challenges are relevant to monolithic (orthotropic or isotropic) walls as well as to masonry walls. Regardless of its type, the analysis of the strengthened wall has to take these aspects into account. At the same time, it has to keep the computational effort reasonable.