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Role of diaphragm flexibility modelling in seismic analysis of existing masonry structures

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ABSTRACT

Numerical modelling considering inelastic response often becomes essential for seismic analysis and assessment of existing masonry structures. Post-earthquake surveys and past experimental studies have demonstrated that flexible diaphragms significantly alter the seismic behaviour of masonry structures. The absence of a rigid diaphragm alters the seismic performance of a structure due to local mechanisms or out-of-plane actions that could compromise the global in-plane capacity. Consistent inferences from different numerical modelling approaches for masonry structures with flexible diaphragms have however been elusive in previous research. Macro-element (or equivalent frame) modelling and non-linear finite element modelling approaches have important differences, particularly in the way interactions between out-of-plane actions and in-plane shear response can be modelled, and in the way they can represent flexible diaphragms. The current paper examines the role of diaphragm flexibility modelling in the global seismic performance of existing masonry structures through a numerical study. Differences observed in the results of equivalent frame modelling versus non-linear finite element modelling, for a set of representative structural models with rigid and flexible diaphragms, under both static and dynamic analyses, are examined. The structural models examined range from single-storied to multi-storied (G + 2) and plan symmetric to asymmetric configurations. The approach to modelling diaphragm flexibility in equivalent frame models is also discussed. Significant differences between approaches imply repercussions on seismic assessment and retrofit design for existing masonry structures.

1. Introduction

Masonry is a construction material that has been traditionally used for load-bearing walls, and more recently for infill non-structural walls. However, in most countries, masonry is still used as a non-engineered solution with little emphasis on its earthquake resistance, despite the availability of norms for earthquake-resistant design and detailing. In an earthquake, the structure is subjected to a series of cyclic displacements, which often cause additional bending and shear stresses in walls that could eventually lead to their damage and collapse. In this regard, masonry structures without seismic-resistant features, have demonstrated poor performance in most earthquakes (e.g. Sikkim 2011, Nepal 2015, Myanmar 2016).

Out-of-plane damage or failure is recurrent due to the lack of specific structural features that provide greater out-of-plane resistance (see Fig. 1). The presence of a flexible diaphragm is identified as an important weakness from post-earthquake surveys worldwide, while the presence of a rigid diaphragm is a major factor identified for satisfactory seismic performance. A flexible diaphragm deforms in-plane when subjected to lateral loads, it is incapable of transmitting torsional forces, and distributes lateral loads to the vertical wall elements in proportion to the tributary area associated for vertical load distribution. Past analytical and experimental research [1–7] has shown that the in-plane stiffness of the floor diaphragm and its connections with the walls affects the seismic behaviour of masonry structures. Proper connection (with anchors, for example) of a stiff diaphragm to the load-bearing walls ensures that lateral displacements are distributed to walls in proportion to their stiffness, thereby ensuring box action. Typically out-of-plane actions trigger local mechanisms, but not global instability, as global seismic capacity is dependent on in-plane mechanisms. This observation has led to the modelling assumption that out-of-plane and in-plane responses do not interact, which also forms the basis of several non-linear analysis approaches for masonry. Independently, approaches based on kinematic limit analysis are used to estimate vulnerability to out-of-plane mechanisms. However, the global capacity could be compromised by these so-called “local mechanisms” and bidirectional effects could potentially reduce pure in-plane shear capacity of masonry walls. There could be three possible scenarios

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Fig. 1. Recurrent seismic damages in masonry structures (Nepal earthquake, 2015).

when a load-bearing wall is subject to seismic displacements. Out-of-plane displacements do not cause any mechanisms in the walls, in which case the wall continues to resist axial and in-plane lateral actions, unaffected. Considering the out-of-plane stiffness and strength contribution in the global model will increase the total base shear. If out-of-plane displacements cause the wall to collapse (i.e. a fully-formed local collapse mechanism), neglecting the out-of-plane effects in the modelling could be on the conservative side. On the contrary, if out-of-plane displacements cause cracking in the wall, but no collapse, then the wall would have reduced capacity to resist axial and in-plane lateral actions. Disregarding the interaction between the out-of-plane and in-plane actions in a global model could be on the non-conservative side, with respect to base shear capacity, neglecting out-of-plane strength contributions. Simplified analytical estimates of global in-plane capacity, such as those based on the storey-shear mechanism approach, also do not take into account interactions of out-of-plane displacements with the in-plane shear capacity.

Regardless of the analytical approach adopted, modelling a heterogeneous material such as masonry, whose behaviour is sensitive to the orientation of bed joints to the direction of load [8], is challenging. Various structural modelling approaches adopted include detailed micro-modelling, simplified micro-modelling and macro or smeared modelling [9–11]. In the micro-modelling approach, the non-linear behaviour of the brick unit, mortar and interface are all explicitly modelled, while in macro-modelling, masonry is represented as an equivalent homogenised material. Knowledge of the mechanical properties of the units, joints and interface prove to be a serious hindrance in adopting the micro-modelling approach, as argued in the literature [9], which may be suitable only for structural components subjected to strongly heterogeneous states of stress and strain.

Another modelling approach that has gained popularity is the macro-element or equivalent frame approach in which the non-linear behaviour of the wall with openings is represented by non-linear force-displacement relations of vertical and horizontal deformable panels, namely piers and spandrels, connected by rigid nodes. In addition to geometrical characteristics, the macro-element is assigned material parameters such Young's modulus, shear modulus, masonry shear strength, bed-joint cohesion, global friction coefficient, and parameters controlling pre-peak and post-peak softening in the force-displacement relation. The analysis method in the macro-element tools typically neglects out-of-plane effects and their interaction with global response. The results obtained from macro-element analysis are comparable to sophisticated micro-modelling analysis without the computational load. A number of macro-element based computer programs, such as Tremuri [12,13], RAN [14,15] and SAM [16] to perform seismic analysis and assessment of masonry buildings are available today. However, as out-of-plane effects are neglected in the modelling, the resulting seismic capacity could be overestimated, leading to a non-conservative seismic assessment.

This paper investigates the effects of a flexible diaphragm on the global behaviour of unreinforced masonry (URM) structures through a comparison of modelling by the equivalent frame approach (Tremuri) and non-linear finite element approach (TNO-Diana), based on both non-linear static and dynamic analysis. Pushover and incremental dynamic analysis (IDA) are carried out on single and multi-storied URM structures.

2. State-of-the art of research

Few researchers have investigated the role of a flexible diaphragm in the global earthquake response of masonry buildings, with important differences between observations from experimental and numerical studies.

Numerical studies have shown that the diaphragm accelerations and fundamental frequency of the building dropped with an increase in diaphragm stiffness ([1–2]). The authors introduced the concept of diaphragm drift ratio (DDR) for seismic evaluation of masonry structures with flexible diaphragms, based on which a 2-DOF analysis tool was developed to evaluate the response in terms of diaphragm accelerations, displacements and fundamental structural frequencies.

Analytical studies conducted by [3] showed that the effect of the flexibility of the diaphragm altered the dynamic properties of structures. From linear dynamic numerical analyses on three structures, viz. a two-storied box structure with timber floor and roof, a two-storied office building with the ground floor diaphragm (timber) being more flexible than the first floor diaphragm (lightweight concrete), and a seven-storied hotel building with plywood diaphragms with steel joists, the authors demonstrated that lateral displacements dropped 50% with increase in the floor stiffness, and lateral accelerations dropped by 54% with increasing diaphragm flexibility. What was interesting to note was the diminishing effect of the torsional mode as the diaphragm flexibility increased.

This is in contradiction to conclusions from numerical studies of [18], who demonstrated through non-linear static analyses, that diaphragm stiffness does not influence the force and displacement capacities for regular two-storied structures, unless there is significant eccentricity between the centres of stiffness and mass of a structure. It must be noted that the comparison is being made between outcomes of linear dynamic analysis and non-linear static analysis.

Micro-modelling of three heritage masonry structures without box action by [4] showed that non-linear static analysis results could not corroborate results from non-linear dynamic analysis, which was able to simulate earlier earthquake damage. Simultaneous adaptive pushover analysis in the longitudinal and transverse directions in the ratio of 100% and 30%, led to concentration of damage in the lintels. It was observed that different types of non-linear static analysis, viz. traditional, modal or adaptive, could not satisfactorily capture effects of out-of-plane actions at the global level.

Sathiparan [5] experimentally investigated the effect of a flexible diaphragm on three single-storied URM structures. Dynamic analyses

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