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# Out-of-plane load–displacement model for two-way spanning masonry walls

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ABSTRACT

This paper describes a methodology for modelling the nonlinear, inelastic load–displacement behaviour of two-way spanning unreinforced masonry walls subjected to out-of-plane loading. The model utilises a simplified macroblock approach that starts with the assumption of a collapse mechanism based on the wall's boundary conditions. It then treats the wall as having zero tensile strength and assumes that the resistance comes entirety from two gravity-based resistance components: elastic rigid block rocking, and inelastic friction, with the total load resistance of the wall taken as the sum of these individual components. Analytical expressions for calculating the load and displacement capacities of the elastic rocking component of response are derived from the principles of statics using an integration approach well suited for the treatment of two-way mechanisms. Expressions for the associated frictional capacity component are obtained using the virtual work method. Comparison of the theoretical load–displacement response with experimentally measured data is favourable as demonstrated using data obtained via quasistatic cyclic tests on two-way spanning walls; the model is shown to provide an acceptable lower bound estimate of actual behaviour. The developed approach could be used to construct pushover curves for a range of different collapse mechanisms and therefore has the potential to be assimilated into a simplified displacement-based seismic design/assessment technique for two-way spanning walls against out-of-plane collapse.



## 1. Introduction

Despite the common perception that unreinforced masonry (URM) structures are brittle, the collapse of URM walls subjected to out-of-plane earthquake loading is governed by geometric stability rather than tensile strength, and the associated load–displacement ($F$–$\Delta$) behaviour can be considered pseudo-ductile. This can be explained by the fact that the formation of cracks and attainment of ultimate load capacity occur early in the overall out-of-plane $F$–$\Delta$ response (illustrated in Fig. 1), which is followed by a reduction in load resistance as a collapse mechanism develops. Once fully cracked, the wall undergoes rocking type behaviour before it eventually becomes destabilised by gravity.

This behaviour is already well established for one-way vertically spanning URM walls (either free standing or simply-supported at top and bottom) whose $F$–$\Delta$ response is nonlinear but elastic, and whose idealised displacement (instability) capacity is equal to the wall thickness [1–4]. By contrast, cyclic loading tests on *two-way spanning* brick walls (walls supported by a combination of their vertical and horizontal edges) have demonstrated that their displacement capacity can be even larger than the wall thickness [5]. This is due to two main reasons: vertically rotating subpanels present in two-way wall mechanisms are not destabilised by gravity, and vertical cracks with brick interlock exhibit bed joint friction which is inherently ductile. The aforementioned cyclic tests as well as shaketable tests on similar half-scale walls [6] have also shown two-way walls to exhibit moderate hysteretic damping due to frictional sources of resistance, which is further beneficial to their seismic performance.

Conventional force-based (FB) seismic design, where the objective is to ensure that the wall's load capacity exceeds the imposed load demand, continues to be the most commonly used method for designing URM walls against out-of-plane failure. From the designer's point of view, this approach is most likely to lead to a favourable outcome (in terms of being able to demonstrate a wall's seismic adequacy) if the ultimate load capacity inclusive of bond strength contribution is known. However, in practical assessment of existing URM buildings it is often difficult to reliably quantify the bond strength without extensive destructive testing. And whilst collapse load capacities can be computed using simplified

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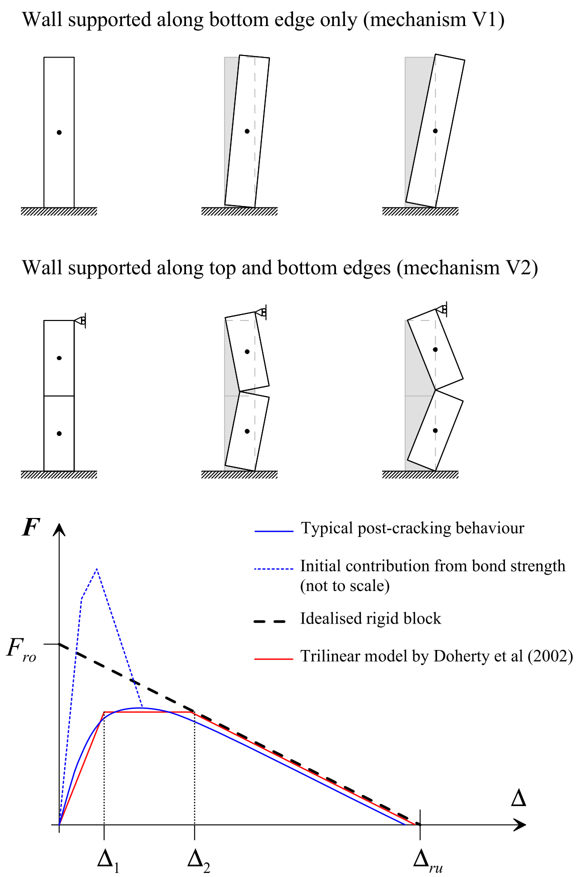


**Fig. 1.** Rocking behaviour of vertically spanning walls. (Only positive displacement side is shown).

limit analysis techniques that ignore bond strength and instead rely on geometric properties for input (e.g. [7,8]), these capacities can often be too low to demonstrate adequacy despite the wall having additional displacement capacity which may save it from collapse under earthquake excitation. Therefore, it is of considerable practical interest to develop an alternate tool for out-of-plane URM wall design/assessment that does not rely on knowledge of the bond strength and which allows for this reserve capacity to be utilised.

Recent trends in seismic design of ductile structural systems have seen a move away from force-based (FB) techniques and toward displacement-based (DB) methods [9], where the design objective is to ensure that the displacement capacity exceeds the displacement demand. Amongst the appeal of DB philosophy is that by accounting for the full displacement capacity, it avoids some of the aforementioned over-conservatism inherent in the FB approach. The fundamental feature of the DB method is that it estimates the structural period using a secant stiffness at the target level of displacement response (instead of using the initial elastic stiffness with subsequent application of load reduction factors to account for ductility effects as is done in FB design). This framework can be implemented in various forms such as direct DB design [10] or the capacity spectrum approach [11]; however, each relies on the ability to construct a $F$–$\Delta$ capacity curve for the structure (in this case the wall).

Considerable progress has already been made toward development of DB methodology for vertically spanning URM walls subjected to rocking. The associated $F$–$\Delta$ capacity rules can be broadly categorised into two types, as illustrated in Fig. 1. The first is based on idealised rigid block treatment characterised by linear-descending branches in the positive and negative $\Delta$ domains with a discontinuity at $\Delta = 0$. The dynamics of such a system were originally described by Housner [12] and first applied to masonry walls by Priestley et al. [13] and further developed since by others [14–16]. The second type of treatment incorporates an initial linear elastic branch to account for non-rigid behaviour, for example using bilinear or trilinear rules [2,17–19].

Extension of DB methodology to two-way spanning walls has lagged behind, largely due to the lack of a suitable and experimentally validated model to describe the load–displacement behaviour. Promising progress has however been made on this topic recently by Lagomarsino [19], who developed a generalised procedure for constructing pushover curves for multiple-block rocking mechanisms. The present paper aims to provide further contribution by proposing a technique for constructing pushover curves for a common class of two-way wall collapse mechanisms, which accounts for the nonlinear, inelastic nature of the response, and which can subsequently be used as the basis for a DB methodology for this class of walls.

## 2. Wall configurations

Before the analytical $F$–$\Delta$ relationship formulation is described in Section 3, the present section will overview the wall configurations that can be catered for.

### 2.1. Support conditions and collapse mechanisms

The proposed model starts with the user postulating a collapse mechanism based on the wall's geometry and boundary conditions. Fig. 2 illustrates the particular out-of-plane collapse mechanisms which are considered in this paper. This family of mechanisms (referred to here as type K) is characterised by diagonal cracks that radiate from corners at which supported edges intersect, and is the most common class of mechanisms associated with mortar-bonded two-way spanning walls as evidenced through a multitude of experimental studies (e.g. [5,6,20–23]). These mechanisms are also embodied in different variations of the plastic analysis method for predicting the ultimate strength of two-way URM walls, including methods prescribed by the Australian Standard and Eurocode 6 [24,25].

The boundary conditions necessary to generate these mechanisms include translational support at the bottom edge and at least one vertical edge. The top edge can be either free (type K1 mechanisms) or restrained (type K2 mechanisms). For conciseness, Fig. 2 shows the wall to be supported along both of its vertical edges; however, each mechanism can also have a form where only a single vertical edge is supported, which is equivalent to considering only one half of the shown deflected shape on either side of the vertical line of symmetry.

It should be mentioned that a wall with a particular set of boundary conditions can potentially undergo additional types of collapse mechanisms to those considered here [7,8], and that since the method adopted is a form of upper bound limit analysis, in a design situation it may be necessary to check a wall against several alternate possible forms to identify the critical one. A study comparing collapse loads computed using different types of two-way mechanisms in walls free at the top edge has shown that mechanism K1 tends to be kinematically favoured in walls with relatively strong bond prior to crack formation [26]. By contrast, walls with zero or low bond strength are more likely to develop mechanisms characterised by diagonal cracks propagating inwards in a 'V' shape (such as mechanisms type D and G dealt with in [7,8]). Although this paper deals solely with type K mechanisms, the general