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Review article

Concrete walls weakened by openings as compression members: A review

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ABSTRACT

The purpose of this paper is to review the advances that have been made in the design of monolithic and precast reinforced concrete walls, both with and without openings, subject to eccentrically applied axial loads. Using the results of previous experimental studies, a database was assembled to enable statistical assessment of the reliability of existing design models. Several design aspects are highlighted, including the size and position of openings, and the roles of boundary conditions and geometric characteristics. In addition, the performance of fiber-reinforced polymers in strengthening wall openings is discussed. Overall it is found that design codes provide more conservative results than alternative design models that have been proposed in recent studies. Research into the strengthening of walls with openings is still in its early stages, and further studies in this area are needed. The paper therefore concludes by highlighting some areas where new investigations could provide important insights into the structural behaviour of strengthened elements.

Contents

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1. Introduction

Sustainable social development requires a safe, functional and durable built environment. Many structures around the world are made of reinforced concrete (RC), most of which were built before 1970 [1]. Functional modifications of these structures are common because existing structures must often be adapted to comply with current living standards. Such modifications may include the addition of new windows or doors and paths for ventilation and heating systems, all of which require openings to be cut into structural walls.

These openings can be divided into three types, namely already existing openings, existing openings that have been enlarged and newly created openings. Creating or modifying openings in walls may change the stress distribution within the wall, adversely influencing its behaviour. It is generally believed that the effects of small openings can often be neglected, while the presence of a large opening usually significantly alters the structural system [2]. However, in the existing literature there is currently no clear delimitation between small and large openings.

Experimental investigations have shown that cutting an opening into an RC wall decreases its ultimate load capacity, requiring the wall to be upgraded [3,4]. Traditionally, two methods have been used to strengthen RC walls with openings, these being either to create a frame around the opening using RC/steel members [5] or to increase the cross-sectional thickness [6]. Both methods increase the weight of the strengthened elements and may cause significant inconvenience by limiting the use of the structure during repairs. A superior alternative that has been used successfully in diverse contexts [7–10] is to use fiber-reinforced polymers (FRP) as the externally bonded material. This technique requires that thin laminates or bars be bonded to the surface of the structure using an adhesive to form a composite material.

The following sections provide a review of contemporary wall design methods that have been included in various design codes [11–14]. Two different design methods can be identified in these documents: (1) a simplified design method and (2) a method based on column theory; the latter is arguably the more rational approach. Although the simplified method is straightforward to implement, its applicability becomes limited when lateral loads need to be considered because in such cases the resultant of all loads on the wall must be located within the middle third of its overall thickness. As a result, the total load eccentricity must not exceed one sixth of the wall's thickness. In this way the walls may be considered as reasonably concentrically loaded [15]. The column method represents a viable alternative that provides more accurate results.

The purpose of this paper is to review the considerable advances that have been made in the design of concrete walls, both with and without openings that are subjected to eccentric axial loads. Additionally, the performance of FRP-strengthened walls is discussed on the basis of earlier studies. Design codes and research studies from across the world were taken into consideration in the analysis. Several aspects are highlighted, including the size and position of the openings, and the roles of boundary conditions and the wall's geometric characteristics (i.e. slenderness $\lambda = H/t$, aspect ratio $\delta = H/L$ and thickness ratio $\eta = L/t$, where H, L and t represent the wall's height, length and thickness, respectively).

A statistical analysis of available models was performed on a database collected by the authors, and is presented in this paper. The outcome of this study provides an overview of the performance of current design models and identifies research gaps. Overall, design codes were found to provide more conservative results than recent design models proposed in other studies. Research into the strengthening of RC walls with openings is still at an early stage, and further studies are undoubtedly required in this area. The findings presented herein will be used to define a new experimental programme that aims to characterize the behaviour of axially loaded RC walls strengthened with FRP; the results of these investigations will be presented in a future publication.

2. Previous experimental work

The results of 253 experimental tests on RC walls reported in the literature were compiled in a database, which is presented in Appendices A1–A3.

In line with the aim of this study, the database contains information on walls that were loaded gravitationally with uniformly distributed forces applied eccentrically at a maximum of 1/6 of their thickness. Tests on walls loaded gravitationally with eccentricities greater than 1/6 of their thickness have also been reported in the literature [16,17]. However, these results are omitted from the database because the design of such walls is not compatible with current industry standards. Data for walls that failed before reaching their ultimate capacity due to incorrect laboratory manipulation were also omitted.

2.1. Database description

The database is organized into six different sections:

(a) Name of authors and citation.
(b) Original description of the test as presented in the cited reference.
(c) Geometrical characteristics of the tested wall: height (H), length (L), thickness (t), number of steel reinforcement layers (n).

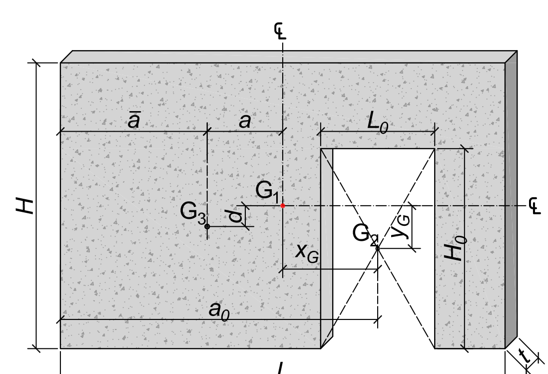

Fig. 1. Geometry of a wall with openings (G3 = centre of gravity of wall with opening, G1 = centre of gravity of solid wall, G2 = centre of gravity of opening) (adapted from [18]).