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Crack development in transverse loaded base-restrained reinforced concrete walls

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ABSTRACT

The prediction and control of crack widths in reinforced concrete structures has been the subject of research for many years. However, there is still a lack of consensus on the design of reinforcement for crack control in walls with edge restraint. The paper describes an experimental programme undertaken to investigate the influence of early-age thermal contraction and long-term shrinkage on cracking in four edge-restrained reinforced concrete walls loaded in bending about their major axis. Bending was introduced as a result of initial preload as well as restraint of deflection due to volumetric change. The walls measured 3500 mm long by 180 mm thick with heights of 500 mm and 750 mm. The paper highlights the main findings of the experimental programme and presents the results of nonlinear finite element analysis that was carried out to investigate the effects of wall geometry and reinforcement ratio on crack widths in edge-restrained walls. Results suggest that crack widths in edge-restrained walls are significantly influenced by the wall geometric properties such as wall aspect ratio and wall height which are only indirectly accounted for through the restraint factor in crack width calculations to EN 1992.

1. Introduction

Following casting, concrete experiences volumetric changes due to early-age thermal (EAT) strain, early-age (EA) autogenous shrinkage and long-term (LT) drying shrinkage. Restraint of free volumetric contraction induces tensile stress which can cause cracking. Unless controlled by sufficient reinforcement, cracking adversely affects durability, aesthetics and water tightness resulting in great cost to the construction industry [1]. This paper focuses on cracking in edge-restrained reinforced concrete (RC) walls and is of relevance to the design of water resisting and retaining walls cast on stiff bases.

Previous experimental studies of cracking in edge-restrained RC walls are limited and unrepresentative of practice due to tests being carried out on reduced-scale walls with either micro-concrete and reduced bar diameters [2] or mortar mixes [3–5]. Where extensive monitoring of field walls has been carried out [4,5], available information is incomplete. This paper develops an improved understanding of cracking in RC edge-restrained walls on the basis of laboratory tests and nonlinear finite element analysis (NLFEA).

Cracking in RC walls with edge restraint is much less researched than cracking in end-restrained members and as yet there is no consensus on the mechanism of crack control in edge-restrained members [6]. A key difference between edge and end restraint is that axial force is constant along the length of end-restrained members but not edge-restrained members where cracking occurs at locations of high restraint. It is convenient to define the degree of restraint in terms of a restraint factor R calculated as follows:

$$R = \frac{\varepsilon_{free} - \varepsilon_{total}}{\varepsilon_{free}} \quad (1)$$

where ε_{free} and ε_{total} are the free and total strains respectively.

Research [7,8] shows that restraint is greatest at the centre and near the base of edge-restrained walls, with restraint decreasing vertically with height from the base and horizontally with distance from the wall centreline.

Stoffers [2] investigated shrinkage induced cracking in edge-restrained RC walls. He examined linear elastic stress distributions in walls constrained to remain straight and showed that tensile stresses (resulting from restraint) only develop in the upper edge of walls with aspect ratios greater than 1.5. He tested micro-concrete walls measuring 375 mm high by 60 mm thick with aspect ratios L/H of 6.7 and 8 that were either constrained to remain straight or free to curve on contraction. In walls constrained to remain straight, crack widths increased with height

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Nomenclature

c	cover to longitudinal reinforcement	R	external restraint factor
f_{ct}	concrete tensile strength	R_a	degree of restraint after cracking
f_{cm}	mean concrete cylinder compressive strength	R_b	degree of restraint before cracking
f_{cu}	measured concrete cube compressive strength	$\propto_t$	coefficient of thermal expansion
f_{yk}	characteristic yield strength of steel reinforcement	δ	measured deflection
h	wall thickness	ε_{free}	free strain in unrestrained member
h_e	element size	ε_R	restrained strain
s_{av}	average crack spacing	ε_{total}	total strain
s_{max}	maximum crack spacing	ε_u	ultimate concrete tensile strain
s_{min}	minimum crack spacing	$\mu\varepsilon$	microstrain = 1×10^{-6} mm/mm
w_{max}	maximum crack width	ν	Poisson's ratio
y	vertical distance from neutral axis of wall uncracked section	ρ	steel ratio based on area of concrete in tension $(= A_s/A_{ct})$
A_{ct}	area of concrete in tensile zone	$\Delta\varepsilon_r$	strain induced by stage 1 loading
A_s	area of tension reinforcement	$\Delta\varepsilon_{max}$	calculated extreme fibre strains induced by stage 1 loading
E_c	elastic modulus of concrete	$\varnothing$	reinforcement bar diameter
E_s	elastic modulus of steel reinforcement		
G_f	fracture energy		
H	wall height		
L	wall length		

from the base with the largest crack widths occurring at the top of the wall where crack spacing was greatest. Reinforcement had a greater effect on crack widths in walls constrained to remain straight than walls free to curve where curvature induced compressive flexural stresses in the upper part of the wall. In his free to curve walls, Stoffers observed crack widths to increase up to a height of approximately 200 mm from the base and then decrease with increasing height from the base.

Kheder and his co-workers [3–5] showed that crack widths in edge-restrained walls are proportional to the change in restraint on cracking defined as $R_b - R_a$ where R_b and R_a denote the elastic restraint factors before and after cracking. Kheder [5] used two-dimensional (2D) elastic finite element analysis (FEA) to show that $R_b - R_a$ increases with wall aspect ratio. He also developed idealised diagrams of $R_b - R_a$ for the calculation of crack width. He [5] concluded that where possible, walls should be constructed with aspect ratios between 1 and 3 to reduce the amount of reinforcement required for crack control. Kheder also observed crack widths in base-restrained walls of the same aspect ratio to increase with wall height [3–5]. Consequently, the reinforcement ratio required for crack control in walls of the same aspect ratio increases with wall height. Correlation is also observed between the location of maximum EAT crack width and maximum temperature drop [9,10].

Experimental and field data from studies described in this section led researchers to propose equations for estimating crack widths in edge-restrained RC walls. Notably, the equations of Stoffers [2] and Kheder [3–5] include wall height and aspect ratio in the calculation of crack spacing unlike the superseded UK code BS 8007 [11] and EN 1992 [12,13].

2. Experimental details

2.1. Introduction

As previously discussed, very limited experimental and field data are available on cracking in edge-restrained RC walls. To this end, the authors tested four edge-restrained walls (E-W1 to E-W4) in the Structures Laboratory of the Department of Civil and Environmental Engineering at Imperial College London [14]. In order to simulate a wall constrained to remain straight, vertical deflections due to concrete volumetric change were restrained as described in Section 2.5. The lateral forces induced by vertical restraint caused bending to develop in the walls. Additionally, transverse preload was applied to ensure subsequent restraint induced cracking. The preload compensated for the flexibility of the vertical restraint and, in the case of walls E-W1 to E-W3, was sufficient to cause immediate cracking. Consequently, tests E-W1 to E-W3 examined the effect of volumetric change on walls precracked in bending. However, the majority of cracks formed in all walls due to restrained shrinkage. The walls were monitored for a minimum of two months for EAT and LT shrinkage cracks. The average air temperatures varied between 20 °C and 27 °C, and the relative humidity between 40% and 60% over the duration of the test programme. The test results are used to develop an improved understanding of EAT and LT cracking in edge-restrained walls and to validate NLFEA models, which are subsequently used to carry out parametric studies of variables not considered in the laboratory tests.

2.2. Testing arrangement

The test setup (Fig. 1) consisted of a RC wall cast against a hot rolled steel universal column (UC), which provided edge restraint. A steel section was chosen for edge restraint because steel, unlike concrete, is not subject to creep or shrinkage. The clearly defined restraint condition simplified data interpretation as well as NLFEA modelling (described in Section 3.3). A 150 mm kicker was cast onto the UC at least one week prior to casting the wall above to simulate the boundary conditions of a wall cast onto a concrete base. The kicker increased the base restraint provided by the UC and reduced heat losses through the UC. The kicker was connected to the UC by pairs of 19 × 100 mm shear connectors at a close spacing of 100 mm chosen to minimise slip between the UC and kicker.

2.3. Design of specimens

Key design requirements were that the walls needed to be sufficiently long for multiple cracks to develop and the restraining UC stiff enough to cause cracking. Walls E-W1 and E-W2 measured 3500 (L) × 180 (h) × 750 mm (H) giving an aspect ratio above the