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Shear failures in reinforced concrete members without transverse reinforcement: An analysis of the critical shear crack development on the basis of test results

Francesco Cavagnis, Miguel Fernández Ruiz *, Aurelio Muttoni

École Polytechnique Fédérale de Lausanne, Station 18, CH-1015 Lausanne, Switzerland

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ABSTRACT

Shear in concrete members without transverse reinforcement can be carried by various potential shear-transfer actions, whose activation depends much on the actual cracking pattern and kinematics at failure. Failures can occur in a progressive manner (at the end of a stable propagation of a critical shear crack) or in a sudden manner (by an unstable progression or development of a new crack). In addition, the development and shape of the failure crack may also be very different from case to case. These differences influence which shear-transfer actions may be governing for a given member and loading situation. Despite the large number of specimens tested in shear, almost no information on the actual crack development during the process of failure is yet available. This paper presents the results of an experimental programme consisting of thirteen beams. The tests were designed to investigate different structural systems and loading conditions commonly found in practice (cantilevers with concentrated and distributed loading, single span beams with distributed loading and continuous beams). The cracking patterns and their associated kinematics were tracked in detail by using photogrammetric techniques at high frequencies during testing and particularly during the process of failure, providing data on the actual crack development leading to shear failure. The observations show that very different cracking patterns may be found and that they might be also developed in different manners. The results are interpreted with reference to the measured crack kinematics and related to the various potential shear-transfer actions, with the aim of providing a useful material towards the development of rational approaches for shear design.
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1. Introduction

Shear design has attracted significant research efforts since the first constructions in reinforced concrete. Particularly, in the case of members without transverse reinforcement, shear is acknowledged as a failure mode potentially governing the design at ultimate limit state and being particularly critical due to its limited capacity of deformation and brittleness. Contrary to design of beams with transverse reinforcement, where consistent design methods based on equilibrium solutions were early developed [1–4], shear design of one-way slabs and beams without transverse reinforcement has mainly remained based on empirical equations in many codes of practice [5,6].

Despite the lack of a generally-accepted mechanical approach, significant research efforts have been devoted in the last decades on the phenomenon of shear-transfer in reinforced concrete [7–11,13–15]. These investigations have allowed understanding the basic shear-transfer actions in reinforced concrete members and have led to the development of mechanical models for shear design. These models have reached a certain level of maturity and are starting to be incorporated into design codes [16–18]. Nevertheless, it is interesting to observe that despite the fact that the different mechanical models predict similar shear strengths, they are not necessarily in agreement on the governing shear-transfer action carrying the load (or their relative significance). A potential reason for this disagreement is grounded on the fact that the mechanical models are usually based on the interpretation of a crack pattern after failure or based on a measured kinematics before it happens. This is the consequence of conventional measurement techniques, that in many cases have not been capable of tracking the crack development during the process of failure. Thus, most times, the interpretation of the shear-transfer actions is performed on the basis of pictures taken prior failure or after it. This might nevertheless have consequences unless the analysis is performed on the basis of a picture taken right at failure

* Corresponding author.
E-mail address: miguel.fernandezruiz@epfl.ch (M. Fernández Ruiz).

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(maximum load), as redistributions amongst the potential shear-transfer actions develop before or during the process of failure (sometimes allowing the member to withstand the applied actions in a stable manner, but sometimes not). In addition, the analysis of the kinematics and cracking pattern during the process of failure yields to a better understanding of the activation of the various shear-transfer actions and failure modes.

In this situation, new measurements techniques are providing a significant breakthrough to obtain better interpretation of the experimental evidence [19]. In particular, digital measurement from high-resolution photography (photogrammetry) constitutes a consistent tool to obtain accurate measurements of strains and crack widths at high frequencies (even higher than 1 Hz). The use of this tool enables detailed investigation of the instants preceding the maximum load and right after it, allowing interpretation of the process during which failure occurs.

In this paper, the results of an experimental testing programme are presented. Other than conventional measurements, photogrammetric techniques were implemented and processed, allowing detailed observations of the actual mechanisms leading to failure. These results are thoroughly explained and related to the shear-transfer actions. It is observed that causes leading to failure are not necessarily the same for the tested members, partly justifying the points of view of different (even contradictory) approaches for mechanical modelling of shear. The experimental programme also investigates the differences that are found between classical laboratory testing (single span beams subjected to concentrated loads) with respect to conditions representative of actual members (continuous beams, distributed loading, compression reinforcement). On the basis of these observations, a critical review of the shear-transfer actions and their role is presented, as well as the agreement and disagreement with some selected mechanical models.

2. Classical definitions of shear-transfer actions and mechanical modelling in reinforced concrete members

The development of mechanical models in reinforced concrete beams without stirrups has been normally performed by accounting for the equilibrium of inner forces developing at a free-body (Fig. 1a) or by considering the role of the potential shear-transfer actions (Fig. 1b–f). Both approaches are in fact related to the principles of the upper- and lower-bound theorems of the theory of plasticity [20]. The former (forces acting on a free-body) investigates on the actions at the edges of the free-body related to the failure mechanism (without any further check inside the free-bodies). The latter usually considers one or more shear-transfer actions as potentially governing, whose maximum strength is calculated on the basis of a licit stress field.

Developing a suitable approach should in fact incorporate both perspectives, accounting both for a suitable stress field and a compatible kinematics allowing activation of the shear-transfer actions. Conventionally, the shear-transfer actions are classified into beam shear-transfer actions (Fig. 1c–f) and the arching action (Fig. 1b). Beam shear-transfer actions require development of tensile stresses in concrete, and allow for the force in the tension chord to vary. They are usually referred as cantilever action (Fig. 1c), residual tensile strength action (Fig. 1d), dowel action (Fig. 1e) and aggregate interlock (Fig. 1f). With respect to full arching action (Fig. 1b), no tensile strength is required in the concrete and the force in the reinforcement remains constant (according to limit analysis, all shear force can be carried without transverse reinforcement by an inclined direct strut [21]). In reality, arching action can also happen combined with the beam shear-transfer actions (Fig. 1f). With respect to the beam shear-transfer actions:

- Cantilever action (Fig. 1c) was acknowledged by Kani as a basic action for shear-transfer [10]. It consists on the development of inclined struts and ties in the concrete between two flexural cracks (Fig. 1c). For a cross-section at the location of a bending crack, shear is carried by the inclination of the compression zone (component V_c in Fig. 1a).
- Residual tensile stresses of concrete (Fig. 1d, component V_t in Fig. 1a). This action can be considered only significant for low cracks openings (or near the tip of the crack).
- Dowelling action (Fig. 1e) requires developing tensile stresses in the concrete cover potentially leading to its delamination. Even after delamination, dowelling action is still possible [11,24] (component V_d in Fig. 1a). In members with compression reinforcement, significant dowelling action can develop provided that the reinforcement is intercepted by the failure crack [24].
- Aggregate interlock (Fig. 1f) allows developing shear and compressive stresses through the cracks due to the roughness of cracked concrete [14,22,23] (component V_a in Fig. 1a). It is an efficient shear-transfer action, yet quite sensitive to the opening of the cracks.

Most of the available design models for shear usually acknowledge one of the previous shear-carrying actions as governing. For instance, the Modified Compression Field Theory [12], can be considered as a theory accounting primarily for the role of aggregate interlock in case of members without transverse reinforcement. The role of the inclination of the compression chord

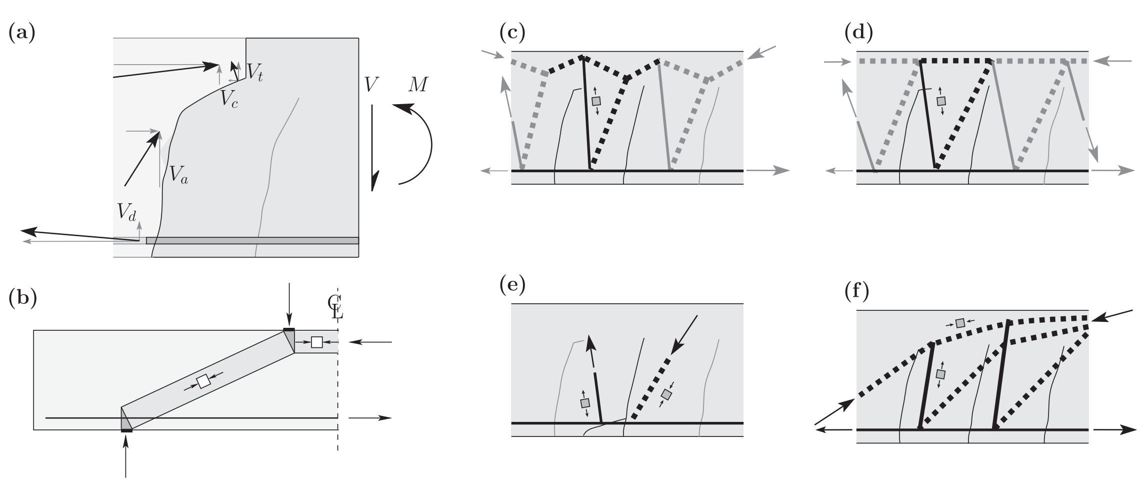

Fig. 1. Analysis of shear transfer actions: (a) free-body equilibrium and internal forces; (b) arching action; (c) cantilever action; (d) residual tensile strength of concrete; (e) dowelling action; and (f) aggregate interlock action.

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