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A multilevel calculation scheme for risk-based robustness quantification of reinforced concrete frames

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ABSTRACT

Structural robustness has become an important research topic in the engineering community since several large failures in the past decades led to the public awareness and indicated the importance to consider structural robustness during the structural design. So far most research has been focusing on structural measures to improve structural robustness and on theoretical methods to quantify structural robustness. However with respect to the analysis of concrete frames, there are only a limited number of examples which try to quantify the achieved robustness level for the available structural measures, such as the development of alternate load paths by membrane action. In this paper both advanced calculation methods and quantification approaches for robustness are combined by a computational efficient calculation scheme which considers different levels of structural idealisation. The developed approach is able to quantify the reliability and structural robustness of planar reinforced concrete frames in an objective way while using a conditional risk-based robustness index and taking into account the developed membrane action. As an illustration the developed calculation scheme is applied and discussed for two alternative designs of a regular office building. The results show the importance of the uncertainty on membrane action effects on the structure in case of an unforeseeable event leading to a notional column removal.

1. Introduction

Recent experimental findings on reinforced concrete beams and one-way carrying slabs have shown the large potential of reinforced concrete structures to develop alternate load paths in case of the notional removal of a load-bearing element [1–6]. Also in steel and composite buildings alternate load paths develop at large displacements [7–9]. The development of these alternate load paths is of particular interest when assessing the structural robustness and should be considered when designing new structures to avoid disproportional damage and progressive collapse. The importance of structural robustness has been underlined by numerous failures in the past decades, such as the notable failures at Ronan Point (1968), the Murrah Federal building (1995) and the World Trade Centre (2001). Typical for these past failures is the fact that due to the lack of structural robustness, a local event with a very low probability of occurrence resulted in very large and disproportional consequences [10]. Although designing a structure to withstand these exceptional events such as terrorist attacks and human errors is impracticable and uneconomical, a beneficial strategy is to allow the development of alternate load paths as much as possible in case of an exceptional local failure. As such one is able to redistribute the loads to other load-bearing elements so that the occurrence of disproportional damage is avoided and the consequences remain limited.

At present much experimental and numerical research has been performed on structural measures to increase structural robustness, such as the development of alternate load paths by membrane action. The influence of alternate load paths on the structural robustness of steel-frame buildings has been investigated by Dinu et al. [11]. On the other hand research has also been focusing on theories to quantify structural robustness by robustness indicators [12] and robustness measures based on stiffness, damage or energy [13]. To quantify the robustness of concrete structures subjected to corroded reinforcement, several robustness indicators and a new robustness definition are discussed by Cavaco et al. [14].

An important next step is to combine the experimental and numerical results of the structural measures with probabilistic techniques to assess the reliability and structural performance of structures in case of exceptional events. A probabilistic approach is necessary since not only the loads of the exceptional event are subjected to uncertainties but also the material properties of the structure. Hence, the structural performance of a building is not deterministic but should be considered

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in a probabilistic way. The importance of uncertainty in the life-cycle performance and optimization of structural systems has been highlighted by Frangopol [15]. An efficient approach to combine reliability assessment and monitoring concepts for structural systems has been developed by Frangopol, Strauss and Sunyong [16]. Xu and Ellingwood [17] performed a probabilistic robustness assessment on the Pre-Northridge steel moment resisting frames while taking into account the uncertainties on the strength of the welded connections. Yu et al. [18] investigated the uncertainty of reinforced concrete frame structures subjected to column loss by combining an experimentally-verified numerical model with Latin-Hypercube samples for the material properties and loads. However the latter study is based on a displacement-controlled push-down analysis with a point load at mid-span which does not represent the real situation as will be discussed in the following. Bucher [19] performed research on the different possible approaches regarding structural design optimization while taking into account robustness. The cost of satisfying design requirements on progressive collapse resistance has been investigated by Charmpis and Kontogiannis [20]. The risk-based robustness index as proposed by Baker et al. [12] has been applied by Narasimhan and Faber [21] on an illustrative example which represented a 40-storey steel frame. Izzudin et al. [22] investigated the structural robustness of a composite frame using a risk-based robustness index while applying a simplified assessment framework. Several guidelines and a theoretical framework on structural robustness were also proposed by the COST Action TU0601 [23].

The above shows that previous research has mainly been focussing on experimental and numerical analysis of membrane action and on the basic principles of robustness which were applied mainly on steel structures. In this work, a computational efficient calculation scheme, which considers different levels of structural idealization, is developed to quantify the robustness of planar reinforced concrete frames using a conditional risk-based robustness index and taking into account membrane action. In Section 2 a brief introduction on membrane action in reinforced concrete elements is given; Section 3 describes the design of two explanatory cases which are designed under gravity loads and wind loads, on which the developed calculation framework is applied; Section 4 presents the developed calculation scheme and discusses the intermediate steps for the investigated explanatory cases; Next, in Section 5, the failure consequences are discussed and the robustness is quantified; Finally, Section 6 addresses some critical points and indicates topics for further research.

2. Membrane action effects in reinforced concrete elements

Traditionally the design of reinforced concrete beams and slabs is based on small deformation theories in which the resistance for bending and shear is the main design criterion. However when one of the supports of such an element is removed due to an exceptional event these elements are subjected to larger deformations which could result in the development of membrane action. Due to the larger deformations, in-plane forces develop which initiate alternative load paths and activate some strength reserve. Analytical and experimental research on the strength reserve by membrane action started mid-20th century focusing on compressive membrane action (CMA) [24–26]. Later experimental research on restrained slabs subjected to large deflections demonstrated the strength reserve of the tensile membrane action (TMA) for small to medium scale specimens with a small thickness [27]. Experiments with respect to tensile membrane action on full scale, one-way carrying slabs were performed by Gouverneur et al. [4]. For two-way carrying unrestrained slabs subjected to large deformations, TMA in the centre of the slab and CMA at the edges of the slab was shown to be the most important load carrying mechanism [28–31]. Research on the behaviour of scaled beams subjected to large deformations was performed by Choi and Kim [2], Kang and Tan [6], Qian and Li [32], Tian and Song [1] and Yu and Tan [3,33], revealing the potential of RC beams to develop beneficial tensile membrane or catenary action. Full-scale tests on beam-column subassemblies were performed by Lew et al. [5] at the National Institute of Standards and Technology (NIST) which also showed the strength reserve by catenary action.

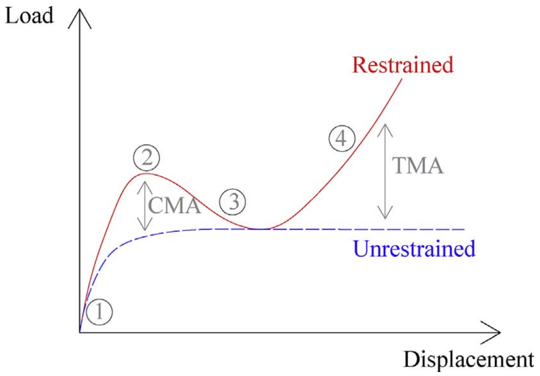

Fig. 1. Load-Displacement behaviour of restrained and unrestrained RC elements.

In general, for a one-way carrying restrained RC element four phases can be distinguished in the load-displacement graph (Fig. 1). First, at small displacements the behaviour of RC elements is dominated by the elastic flexural resistance of the element (phase 1 in Fig. 1). Next, at larger displacements the compressive membrane phase starts as compressive membrane forces are induced due to the restrained outward movement of the edges of the element. For elements with a small slenderness such as beams the latter involves also arching action. These in-plane membrane forces activate a significant beneficial effect as the bending moment – normal force interaction results in a much larger flexural capacity than normally accounted for by methods such as Johansen's Yield Line Theory. Especially in case of elements with a small slenderness, such as beams, the compressive membrane action can govern the maximal capacity of the element. After the maximal flexural load is reached in point 2 of Fig. 1, the resistance of the element starts to decrease and softening is observed in the load-displacement graph due to crushing of the concrete in the compressive zones. This phase is called the transient phase as the membrane forces change from compressive membrane forces to tensile membrane forces during this phase. At point 3 in Fig. 1, which generally corresponds to a mid-span displacement equal to the effective depth of the element, the membrane forces change from compression to tension and the edge restraints start to resist inward movement of the element. At this point the tensile membrane phase initiates and the reinforcement starts acting as a tensile net which enables additional load-carrying capacity (part 4 in Fig. 1). If sufficient reinforcement and ductility is available the resistance can increase beyond the maximal load bearing capacity of the compressive membrane phase. Eventually the element fails due to rupture of the reinforcement and/or crushing of the concrete.

Whether the maximal resistance of the RC element is reached during the compressive or tensile membrane phase depends on the slenderness and boundary conditions of the elements. In most experiments on RC beams some catenary action is observed, which can be mainly attributed to two reasons. First of all, in most cases scaled elements are tested. These scaled elements can deform more easily, which enhances the development of tensile membrane action. Secondly in most experiments a push-down displacement controlled test is used with a point-load at mid-span, resulting in a different internal force distribution compared to uniform loading. For the uniform load case the largest moments and shear forces are located at the end-sections, hence the failure mechanism will be concentrated at the top reinforcement in the end-sections and the element could fail at smaller deformations. This is in contrast with most experimental tests which apply a point load at mid-span. For the situation with a point load at mid-span the moments at the centre and ends of the beam are equal and the shear force is largest at the centre. As a consequence in most experiments the bottom