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Influence of modelling strategies on uncertainty propagation in the alternate path mechanism of reinforced concrete framed structures

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A B S T R A C T

Reliable performance-based evaluation of structures subjected to extreme loading scenarios, which is a function of structural response uncertainty characterization is a vital question. This paper aims to study the major sources of uncertainty in the alternate path response quantities of reinforced concrete framed structures subjected to sudden column removal scenarios. Using global variance-based sensitivity analysis, influence of nonlinear modelling approaches on uncertainty propagation is studied. Sensitivity of structural response quantities to the input uncertainties using plastic analysis with lumped plastic hinges found to be quite distinct compared with those of obtained using fibre-based modelling approaches, where axial–flexural deformation interaction, and in turn, compressive arching action is taken into account. Moreover, uncertainty propagation at different load levels is investigated using nonlinear incremental dynamic analysis (NIDA). Results obtained from displacement-based element (DBE) formulation, and force-based element (FBE) formulation were in good agreement at low to moderate load factors, where use of DBE formulation found to be computationally more efficient. However, at high load factors, where the structure is prone to progressive collapse, FBE formulation provides more reliable solution as the DBE formulation underestimates local response quantities, and in turn, underestimates the probability of failure. Finally, as uncertainty evaluation using fibre-based modelling approaches is computationally expensive, a substructure technique is applied, and influence of structural idealization on uncertainty propagation in structural response quantities is investigated. Results show that structural idealization is an efficient technique for reducing computational costs in terms of probabilistic analysis, especially when hundreds or thousands of simulations are needed to be performed.

1. Introduction

Catastrophic collapse such as those of the Alfred P. Murrah Federal Building in 1995 and the World Trade Center towers on 11 September 2001 have exposed the vulnerability of our societies to the problem of progressive collapse. Such a structural-level problem indicates a situation where a triggering local failure provokes a chain reaction of failures, which results in the collapse of the entire structure or a large part of it, which is disproportionate to the triggering action [1].

Among the proposed direct and indirect design approaches for mitigating the risk of the progressive collapse, the threat independent alternate path method is widely used in the recent research studies. This method provides an insight into the ability of the structure to redistribute the amplified gravity loads through bridging over failed elements. In the last decade numerous research studies were conducted on the nonlinear dynamic redistribution of forces in accordance with the alternate path method. Some valuable experimental investigations can be found in [2–5], where full and half-scale 3D RC structural buildings are tested under column removals. As for the numerical investigations, three typical analytical procedures of Linear Static (LS), Nonlinear Static (NLS) and Nonlinear Dynamic (NLD) are employed. Although the LS analysis is readily feasible in any computer program, it may not be accurate as nonlinearity and dynamic effects are not properly accounted for [6]. The NLS procedure, in which load increase factors are to be multiplied into the load combinations to account for the dynamic effects, is of engineers' interest due to its simplicity compared with the NLD analysis procedure. Nevertheless, the NLD analysis procedure is the most promising method for evaluating the structural response quantities following the instantaneous loss of a load-bearing element. In a NLD analysis procedure, internal forces at the top of the columns to be removed shall be scaled from 100% to zero in a short period of time representing sudden loss of supporting elements. Two major progressive collapse guidelines,

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namely the GSA [7] and the DoD [8] propose plastic analysis using lumped plastic hinges for investigating the problem of force redistribution following instantaneous removal of a vertical load bearing element. Examples of this modelling approach can be found in some research papers such as [4,9,10]. However, such a modelling approach neglects compressive arching action of structural components bridging over failed vertical load-bearing elements. On the other hand, it has been well proved that compressive arching action in laterally restrained reinforced concrete slabs and beams significantly increases the collapse load of the structural members [11–15]. Most of the previous experimental and numerical research studies on the compressive arching action are mainly focused on either 2D planar frames or beam column sub-assemblies such as [16–21]. Examples of 3D NLD evaluation of force redistribution following vertical load-bearing elements can be found in [3,22], where either closely spaced fibre plastic hinges (FPHs) or nonlinear flexibility-based elements are employed to account for the axial–flexural deformation interaction. Despite extensive research work on the inelastic alternate path response of the structures as well as progressive collapse resisting mechanisms, recent works mainly addressed this problem in a deterministic manner. Though, a reliable performance-based evaluation of structures subjected to extreme loading scenarios is a vital question, which is a function of structural response uncertainty characterization. Thus, uncertainties in structural properties, which are the major sources of uncertainty in response quantities are needed to be investigated using sensitivity analysis. The objective of this paper is to study the major sources of uncertainty in the alternate path response quantities of reinforced concrete frames subjected to sudden column removal scenarios. Uncertainties in strength and stiffness related material properties, superimposed dead loads, and damping were studied using variance-based global sensitivity analysis. The influence of modelling strategies on uncertainty propagation is investigated using different nonlinear modelling approaches. In addition, uncertainty propagation is studied at different load factors using nonlinear incremental dynamic analysis (NIDA), where uncertainty propagation in the entire range of structural behaviour from elastic to inelastic and finally extreme plastification state is investigated. As the global sensitivity analysis using Full3D NLD models is computationally expensive, a substructure technique is applied, and uncertainty propagation in response quantities are compared in each level of structural idealization, and at different load levels.

2. Nonlinear finite element modelling approaches

Plastic analysis using lumped plastic hinges and fibre-based modelling using distributed plasticity are two common approaches usually employed in nonlinear analysis of framed structures. As for the nonlinear alternate path analysis, the earlier is suggested by progressive collapse guidelines such as GSA [7] and DoD [8], where beam elements are modelled using Bernoulli beams with localized moment plastic hinges (MPHs). Axial-force/biaxial-moment PMM plastic hinges can be also assigned to the columns to account for the axial-force/biaxial-moment interactions. In a MPH, post-yield behaviour is typically described by a moment–plastic rotation relationship as shown in Fig. 1. Likewise, in a PMM plastic hinge, a 3D interaction yield surface as shown in Fig. 2, is first defined, and then, the post-yield behaviour of the element will be interpolated from moment-rotation curves [23]. Plasticity is only considered in localized rigid–plastic hinges and cracking of RC beam sections cannot be involved automatically. Thus, iterative analysis is required, where appropriate cracking coefficient have to be assigned to the cracked beam sections. Besides, neither MPHs nor PMM plastic hinges account for the axial–flexural deformation

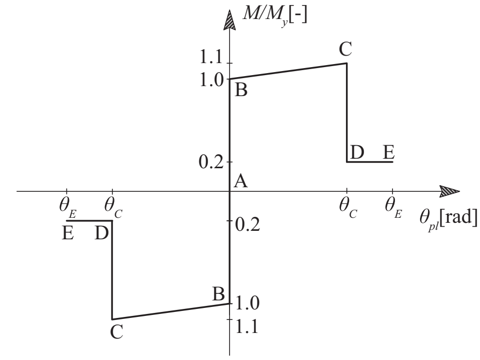

Fig. 1. Moment–plastic rotation relationship in a typical MPH: point B represents start of yielding, point C shows the ultimate flexural capacity, point D illustrates residual strength, and point E corresponds to total failure.

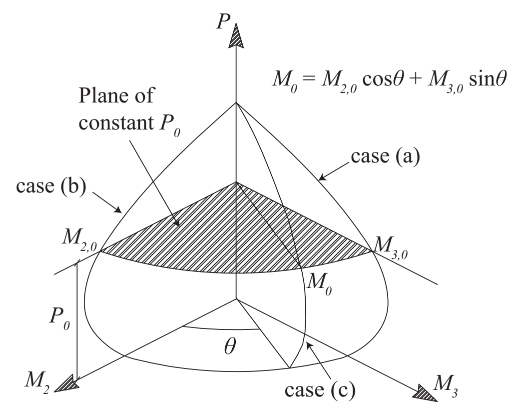

Fig. 2. A typical 3D interaction yield surface for the axial-force/biaxial-moment interaction in a PMM plastic hinge: M_0 is the resultant bending moment, $M_{2,0}$ and $M_{3,0}$ are minor and major bending moments respectively, and θ is the moment angle, case (a): $P - M_3$ interaction curve, case (b): $P - M_2$ interaction curve, and case (c) shows a general PMM interaction curve.

interactions, and in turn, neglect compressive arching action (CAA) contribution in resisting progressive collapse.

Following the instantaneous loss of a vertical load bearing element, beams and slabs associated to the damaged bays start to bridge over the removed column. Subsequently concrete fibres crack at critically loaded beam sections. As cracks propagate, the neutral axis tends to shift towards the compressed fibres, which results in a net tensile strain at the mid-height of beam sections, and in turn, elongation of beams. However, if such an elongation is restrained as it normally occurs in the multi-span framed RC structures due to in-plane stiffness of neighbouring elements, compressive forces will develop to satisfy the axial displacement compatibility. Such a mechanism in reinforced concrete components is called compressive arching action, which is a crucial resisting mechanism that significantly help the structure to resist progressive collapse.

Contrary to the concentrated plasticity approach using MPHs, fibre-based modelling approaches using nonlinear displacement-based element (DBE) and force-based element (FBE) formulations account for the plasticity distribution as well as axial–flexural deformation interaction at sectional level. Furthermore, force redistribution due to cracking and crushing of concrete fibres as well as yielding or rupturing of reinforcing steels can be robustly reflected by assigning realistic uniaxial stress–strain relationships to the concrete and steel fibres at beam–column cross-sections. While in the conventional DBE formulation, solution is derived based on discretization of the displacement fields of the element