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# Modelling of connection behaviour for progressive collapse analysis

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ABSTRACT

The structural robustness of frame structures depends to a considerable extent on the ability of the connections between the main structural elements to transmit the sorts of loading generated following an initial structural damage while delivering the deformations needed to arrest progressive collapse through dissipation of the collapse energy. Therefore, connection performance is, arguably, the most important feature of the problem and accurate modelling of the connection behaviour under the sorts of conditions experienced during progressive collapse is an essential component for any realistic analysis. Based on the component method principles of EC3 and EC4, a mechanical approach for describing the behaviour of bare steel and composite connections for use in progressive collapse analyses is developed herein. Explicit expressions covering the full range of loading – including interaction between the connection bending moments and beam axial load – and problem variables likely to be encountered in practice are derived. Those expressions can be applied in a step-by-step consideration for tracing connection nonlinear behaviour up to failure. The model is carefully validated against both available tests and results obtained from rigorous numerical analyses.



## 1. Introduction

Methods for designing structures to guard against progressive collapse were first introduced into the UK Building Regulations [1] and their supporting National Standards in the aftermath of the well-known Ronan Point collapse in 1968. Over time, similar approaches have been adopted in other structural codes such as the Eurocodes [2]. Those traditional methods – which have essentially remained unchanged until the present – comprise general provisions or prescriptive rules that do not allow for a quantitative assessment of the level of robustness possessed by the structure. Since general interest has significantly heightened following the WTC collapses in 2001, the need for a more scientific understanding of the mechanics of progressive collapse has become more important. Therefore, considerable effort has been focussed on developing and applying the alternative load path method, which offers the advantage of demonstrating resistance to progressive collapse in a quantitative manner by modelling the actual mechanics of the problem. Currently, comprehensive rules and guidance for application of the alternative load path method may be found only in the recent US General Services Administration [3] and Department of Defense [4] guidelines to robustness.

Most frequently, the alternate load path method is implemented through notional removal of a column and evaluation of the ability of the remaining structural members to function as alternative load paths by adequately redistributing the additional loads imposed upon them. Since progressive collapse is a dynamic phenomenon in effect, sudden column removal is considered. By general consensus, the single most important feature of performance is the ability of the connections to transmit the additional loading without exhausting their available deformation capacities.

The level of structural analysis employed to examine the behaviour of the damaged structure may vary from static applications using elastic theory and dynamic load factors to sophisticated numerical approaches that explicitly account for dynamic effects, second-order geometric effects and inelastic material behaviour. Linear static applications have the advantage of being simple to implement in practice but they are arguably insufficient to provide reliable representations and usually result in highly conservative predictions. On the other hand, sophisticated nonlinear dynamic approaches, while being capable of providing accurate descriptions of the key features of response, are extremely demanding in terms of computing capability.

An alternative method that addresses all the essential features of the problem but which does not require unduly complex analyses has been derived at Imperial College London [5]. Only static analysis accounting for material and geometric nonlinearity is required whereas dynamic effects are incorporated through a simplified energy-balance procedure. The analysis step can be conducted using detailed finite element models, while simplified models may also be adopted provided a realistic representation of connection behaviour under the sorts of conditions experienced during progressive collapse is considered.

Basic features of connection behaviour are identified in the following section where particular attention is given to the axial forces generated in the beams by the compressive arching and tensile catenary actions developed during progressive collapse response. A review of previous studies that have focussed on developing the connection moment–

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rotation characteristics to include the effects of axial force in the beam is then provided. The remainder of the paper presents an improved model for describing connection behaviour in progressive collapse that has, in turn, supplied fresh insights into both the role of beam axial load and the physical reasons behind the different types of response observed in the key connection components.

## 2. Key features of connection behaviour in progressive collapse

The column removal mechanism may be modelled based on a three-dimensional consideration of the whole structure or at least, the part of the structure in the immediate vicinity of the removed column. However, lesser levels of structural idealisation are likely be more productive in studying performance of individual components. The double-span condition created by two adjacent beams following loss of the intermediated column as illustrated in Fig. 1 represents a simple and commonly used approach for examining beam and connection behaviour during progressive collapse. Either the intact loaded structure is considered and then column removal is performed, or the damaged unloaded structure is considered and the loading is then applied. Depending on the position of the removed column within the frame, a degree of axial restraint may be provided to simulate interaction with the surrounding structure.

The double-span beam concept has been widely adopted in recent studies of progressive collapse where nonlinear static applications were employed. Some experimental studies considering bare steel beam-column assemblies comprising simple [6–8] or moment [8,9] connection configurations and certain studies accounting for the additional effects of composite action in the beams and/or the connections [10–12] have been conducted over the past few years. Moreover, several numerical studies, each using different software and modelling techniques may be found in the recent technical literature, e.g. [13–16].

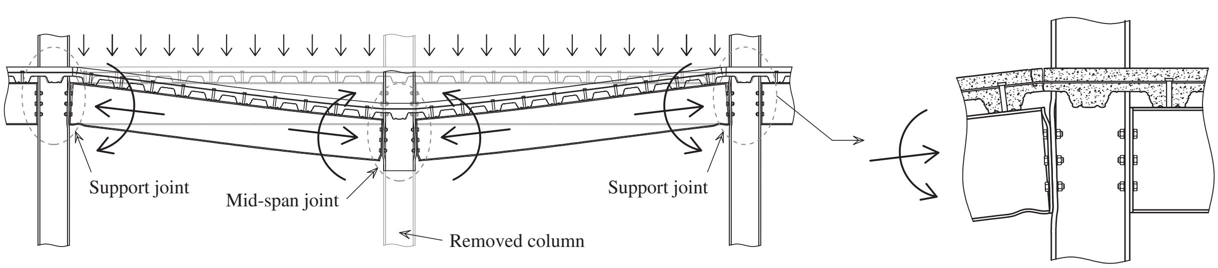
Previous studies have shown that the form of behaviour varies depending on the type of the connections employed. Simple connections such as those consisting of fin-plates, partial depth endplates or web cleats tend to exhibit relatively limited capability for transferring the additional loading imposed by removal of a column. Although such connections are designed to transfer only shear and axial forces, they may essentially be transformed to moment connections following development of prying action between the beam flange and the supporting member when sufficient beam rotation occurs. This usually results in limited connection ductility due to early failure of the most heavily-loaded bolt-rows. On the other hand, semi-rigid or rigid connections that are designed to transfer bending moments may inherently exhibit comparatively enhanced performance.

Axially restrained beams with semi-rigid or rigid connections suffering column loss exhibit the form of load-deflection response described in Fig. 2(a) [17], where the corresponding behaviour in the absence of axial restraint is also presented. The figure describes the full range of behaviour disregarding any deformation limits. In practice however, failure may occur at any stage of the response depending on the available ductility of the connections. The response comprises various phases, where different mechanisms are mobilised in each phase to resist collapse. Following the initial elastic phase which essentially resembles behaviour under normal loading conditions, the post-elastic response (i.e. beyond point 'B' in Fig. 2) is largely governed by material and geometric nonlinearity. During that phase, connections are subject to bending moments as well as axial forces that are generated in the beams due to the effects of geometric nonlinearity and the presence of axial restraints. Various combinations may be seen during the different stages as demonstrated in the typical diagram of Fig. 2(b) [17].

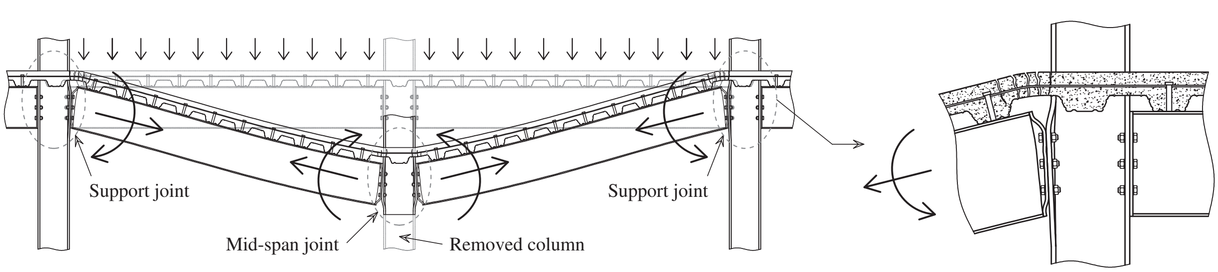
In the compressive arching stage, the beams are subject to axial compression. Both the beam axial compression and the connection bending moments may reach relatively high values during that stage, thus leading to premature instability in some compressive components of the connections as illustrated in Fig. 1(a). The compressive arching effects gradually decrease (i.e. after point 'C') and the beam axial load becomes tensile in the subsequent stages (i.e. beyond point 'D'). As the ratio between the beam axial tension and the connection bending moment increases, bending effects become less significant and connections undergo extensive tensile deformations. Eventually (i.e. following point 'E'), no prying action between the beam compressive flange and the supporting member occurs as illustrated in Fig. 1(b) and tensile catenary action becomes the principal load carrying mechanism.

Therefore, the following features of connection performance are identified:

- The connection deformations may develop well beyond the elastic range.
- Connections are subject to substantial axial forces that may vary disproportionally to the bending moments during the different stages of response.




(a) Compressive arching stage




(b) Tensile catenary stage

**Fig. 1.** Double-span beam condition created by column removal.