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Component-based steel beam–column connections modelling for dynamic progressive collapse analysis

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A R T I C L E I N F O

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A B S T R A C T

A component-based model is developed to predict the dynamic response of bolted-angle connections, such as web cleat connections and top and seat with web angle (TSWA) connections subjected to sudden column removal scenario. This model considers the behaviour of bolted-angles under large tension forces. A failure criterion determined from the test results is introduced into the model for the bolted-angle component to predict the connection resistance. The hysterical behaviour of each component under cyclic loads is also included for ensuring dynamic analysis. The proposed component-based connection models with detailed springs as well as their constitutive laws are implemented within a self-developed finite element programme FEMDYA to validate the model against both static and dynamic test results. A comparison study showed the capabilities of the component-based model in predicting the connection performance. Based on the failure criterion of the connection component, an accurate simulation of the fracture of the connections is conducted. Subsequently, the component model is incorporated directly into two types of 4-storey steel frames to simulate catenary action developed due to the loss of support to a middle column. The analysis results indicate that a value of up to 2.9 should be used as the dynamic increase factor for structures with web cleat connections when incorporating the dynamic effects into the nonlinear static load resistances. It is also shown that the ultimate load capacity of unbraced structure is much smaller than the one in the braced frame due to horizontal movements of adjacent columns under catenary action.

1. Introduction

The importance of design of buildings to mitigate progressive collapse has been well recognised since the partial collapse of Ronan Point apartment building in 1968 in London. One of the major design approaches for prevention of progressive collapse is alternate load path (ALP) method, which has been used in a large number of numerical studies to assess the progressive collapse potential of both steel and concrete structures. A key issue for progressive collapse is to understand that the structural responses to the initial damage of one or more columns involve complicated nonlinear dynamic processes. Sudden column removal is considered as an efficient design scenario for investigation of structural resistance to progressive collapse. More and more analyses have been conducted based on a sudden column removal scenario to incorporate the effects of dynamic load redistributions in structural responses to progressive collapse [1–5].

In addition, many experimental studies showed that the structural connections are essential in prevention of progressive collapse [6–9]. The real connection behaviour should be incorporated in progressive collapse analysis and design. As structural members of a building involved in a progressive collapse are likely to undergo large displacements resulting in excessive demands in joint ductility, the load transfer mechanism and failure criteria of the connections under dynamic loading conditions are of utmost importance. In order to investigate the dynamic behaviour of steel connections subjected to a sudden column removal scenario, experimental tests and finite element (FE) simulations were conducted recently by Liu et al. [10,11] in Nanyang Technological University, Singapore. Three types of commonly used steel beam–column connections were studied, viz. web angle, top and seat with web angle (TSWA) as well as flush end plate. The test and analytical results demonstrated that the dynamic phenomenon had detrimental effects on the connection performance, which resulted in weakening of the structural assemblage. The research data also showed that at large deformation stage, catenary action was mobilised in all the three types of connection to redistribute the associated forces and to resist progressive collapse. The experimental tests and the three-dimensional FE simulations can provide the most realistic connection behaviour under sudden column loss. However, due to exorbitant high cost of the physical

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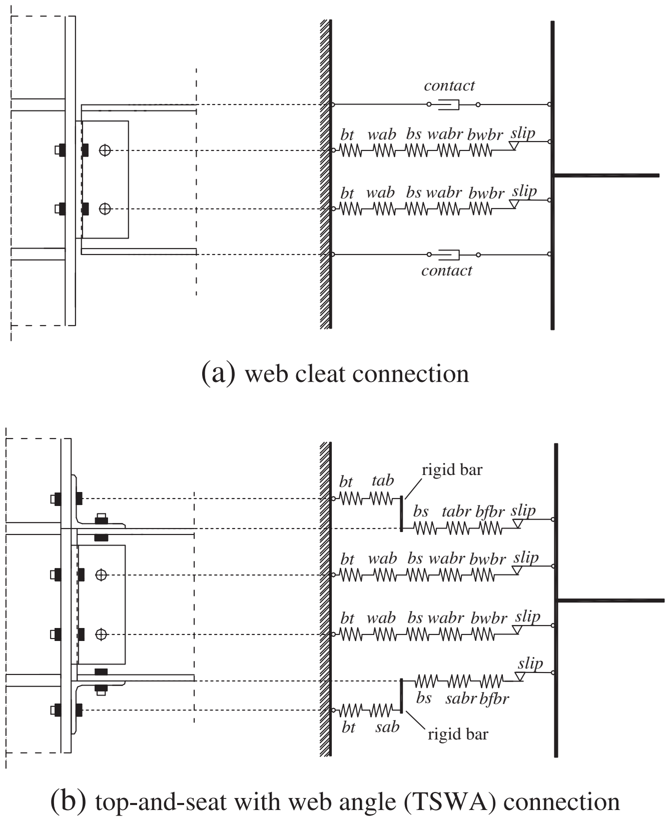

Fig. 1. Complete component-based models for bolted-angle connections.

and extensive computational time required by 3D modelling, these two methods are inapplicable in the design office. A more practical and effective method relies on using component-based approach to model the connection behaviour.

The component-based mechanical joint model decomposes the joint behaviour into a series of components and each of these components is modelled by an equivalent nonlinear spring corresponding to a force–displacement relationship. This model not only represents the stiffness and strength characteristics of all the components of the joint, but also accounts for the interactions of axial forces, shear forces and bending moments co-existing at the beam–column joint. The principles of the component method were based on the experimental and analytical works conducted by Zoetemeijer [12] from 1974 to 1983. After that this method was further developed by a number of researchers. Tschemmernegg carried out a series of works for modelling welded and bolted bare-steel end plate connections [13,14]. The research studies conducted by Jaspart [15] from the University of Liége, Belgium, should be mentioned, in which the available component data were combined as a practical design concept for connections at ambient temperature. Furthermore, the component method has become the standard tool for calculations of semi-rigid joint behaviour with its inclusion into EC3-1.8 [16] for the design of bare steel connections.

Over the years, a significant portion of the research efforts have been devoted to extend the component-based approach to model the connections behaviour under different loading conditions. A hysteretic model of bolted-angle connections was proposed by Shen and Astaneh-Asl [17,18] for seismic analysis of semi-rigid steel frames. Yu et al. [19] developed a component-based model for web cleat connections under elevated temperature, which considered the connection behaviour up to failure. A nonlinear component-based model was developed by Sulong et al. [20] to simulate the response of steel connections under various loading conditions and temperature variations. The model was capable of predicting the behaviour of typical connection types including the end plate and bolted-angle connections for both seismic and fire conditions. Yang and Tan [21] developed a new component-based mechanical model to predict the behaviour of bolted-angle connections until complete fracture occurred. A new failure criterion of the bolted-angle component was also included to determine the connection deformation capacities.

Most of the previous studies on the component-based approach provided approximate estimations of the initial stiffness and the moment resistance of various connections for analyses and design. However, for connections under some complex loading conditions (i.e. fire and progressive collapse), the nonlinear response of each component of the connection and the associated connection failure should also be incorporated into the connection models. However, there are still very limited publications on the modelling of connection behaviour under sudden column loss process. These connection models are critical in structural analysis for assessment of progressive collapse resistance. Therefore, the aim of this study is to present the development of component-based approaches for predicting the dynamic response of bolted-angle (web angle and TSWA) connections. The hysteric behaviour under cyclic loads is included for dynamic analysis and the failure criteria proposed by Yang and Tan [21] are used to determine the connection resistances. The proposed component-based connection models with detailed springs as well as their constitutive laws are implemented in a self-developed finite element programme FEMDYA [22] to validate the component-based connection models against both static and dynamic test results. Based on the proposed component-based connection models, analysis results of two four-storey steel frames show that a value of up to 2.9 should be used as the dynamic increase factor for structures with web cleat connections when incorporating the dynamic effects into nonlinear static load resistances. It is also shown that the ultimate load capacity of unbraced structure is much smaller than the one in the braced frame due to horizontal movements of adjacent columns under catenary action. This indicates that the stiffness of the remaining structural members surrounded to the damaged column has a significant influence on the structural resistance to progressive collapse.

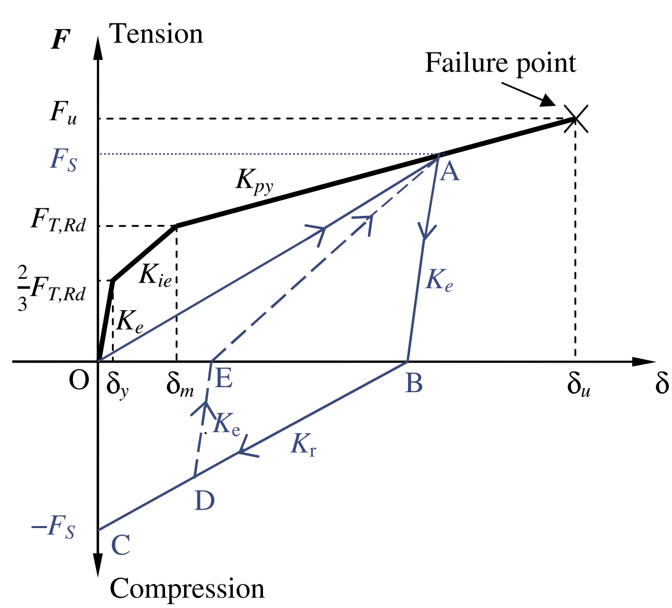

Fig. 2. Hysteric load–displacement relationship of bolted-angle under cyclic loading.