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# System reliability evaluation of steel frames with semi-rigid connections

Huu-Tai Thai [a,d,*], Brian Uy [a], Won-Hee Kang [b], Stephen Hicks [c]

[a] Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW 2052, Australia
[b] Institute for Infrastructure Engineering, University of Western Sydney, Penrith, NSW 2751, Australia
[c] Heavy Engineering Research Association, Manukau, Auckland City, New Zealand
[d] School of Engineering and Mathematical Sciences, La Trobe University, Bundoora, VIC 3086, Australia

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ABSTRACT

This paper presents an accurate and efficient numerical procedure for evaluating the system reliability of steel frames with semi-rigid connections. The ultimate strength and behaviour of the frame were predicted using a refined plastic hinge model due to its computational efficiency, whilst the nonlinear behaviour of semi-rigid connections was captured using a three-parameter power model. The statistical properties for the three parameter power model were obtained based on available experimental results. The sensitivity of reliability to the model error was also studied. Monte Carlo simulation was used to estimate the probability of failure and the reliability index of a system. Two example frames subjected to combined gravity and wind loads were examined and their system reliability indices for both strength and serviceability limit states were evaluated based on the randomness in loadings, material and geometric properties and semi-rigid connections. The results indicate that the frame reliability is strongly affected by semi-rigid connections.



## 1. Introduction

In conventional analysis and design of steel frames, the behaviour of beam-to-column connections is treated as either pinned or rigid joints to simplify the analysis and design process. However, most connections used in practice are of a semi-rigid and partial strength type whose behaviour lies between these two extreme cases. The effect of semi-rigid connections on structural analysis does not only change the moment distribution along the beams and columns, but it also increases the frame drift due to second-order effects. Therefore, modern design codes such as Eurocode 3 (EC3) [1] and the AISC-LRFD Specification [2] permit the consideration of the semi-rigid behaviour of these connections to reflect the actual situation. The application of member-based design codes considering the effects of semi-rigid actions is rather tedious due to the calculation of the effective length factor. Therefore, over the last two decades, considerable effort has been devoted to developing advanced analysis and design methods which can capture the ultimate strength of a whole structure and thus eliminate the need for individual member capacity checks (see Refs. [3–15], among others).

The reliability of a structure measured by its probability of failure is an important factor that a design engineer has to take into consideration due to the uncertainties related to loads, material and geometric properties. The reliability of a single member in steel frames has been studied over the last four decades for the purpose of calibrating member-based design codes [16–20]. Comparison between the member and system reliabilities reveals that the reliability of a whole structural system is always higher than that of the member which governs the design of the structure due to the beneficial effect of the force distribution [21]. The difference between the system and member reliabilities depends on the structural configuration, the degree of redundancy and the dead-to-live load ratio. A number of studies have been carried out to assess the system reliability of steel frames using different methods such as first-order reliability method (FORM) [22–25], neural networks and Monte Carlo simulation (MCS) [26–30] and the FORM-based response surface method [31]. However, only three studies [22–23,28] considered the effect of semi-rigid connections and these possessed some limitations. For example, all these studies ignored residual stresses and initial geometric imperfections. Frangopol et al. [22] and Hadianfard and Razani [28] also neglected the nonlinear behaviour of the frame and connections as well as the uncertainties in the connection model. Since the exclusion of residual stresses, geometric imperfections and nonlinear behaviour in the reliability analysis may lead to an improper assessment of frame stability [32], the results obtained in existing studies may be unreliable. In addition, the effect of the model error associated with the prediction of the frame strength was not studied in existing works.

In this paper, an accurate and efficient numerical procedure accounting for residual stresses, geometric imperfections and the nonlinear behaviour of the frames and connections is proposed to evaluate the system reliability of semi-rigid steel frames. In this procedure, the failure probability and the reliability index of a system are estimated using MCS, whilst the ultimate load-carrying capacity of frames was predicted using a refined plastic hinge element and a three-parameter power model. The benefit of the proposed method is its accuracy and

* Corresponding author.
*E-mail addresses:* t.thai@unsw.edu.au, tai.thai@latrobe.edu.au (H.-T. Thai).

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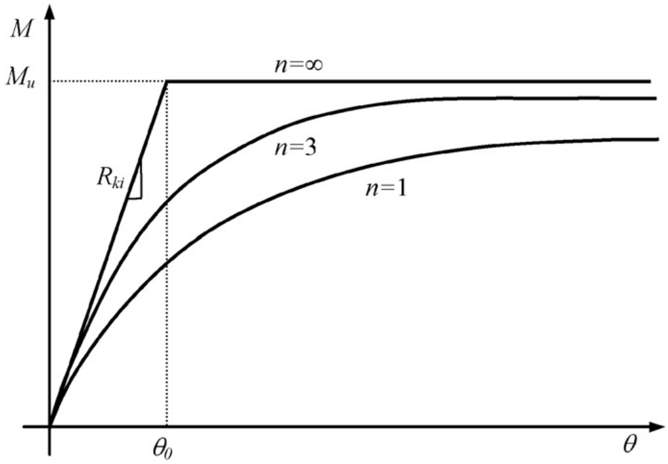


**Fig. 1.** Moment–rotation of the power model.

computational efficiency, and thus it can be used for structural engineering problems with many random variables and very small values of failure probability. Two frames subjected to combined gravity and wind loads were examined and their reliability indices were evaluated for both the strength and serviceability limit states.

## 2. Deterministic advanced analysis of semi-rigid steel frames

### 2.1. Modelling of beam–column members

Among advanced analysis methods, the refined plastic hinge method proposed by Liew [3] is the most efficient one for predicting the ultimate strength of steel frames. In this model, the geometric nonlinearity due to the interaction between the axial force and bending moments ($P-\delta$ effect) is accurately captured by using stability functions. The gradual yielding effect due to residual stresses is considered using the tangent modulus concept $E_t$ proposed by Liew [3]. The gradual stiffness degradation of a plastic hinge due to flexure is represented by a parabolic function which is associated with the yield surfaces at the two end

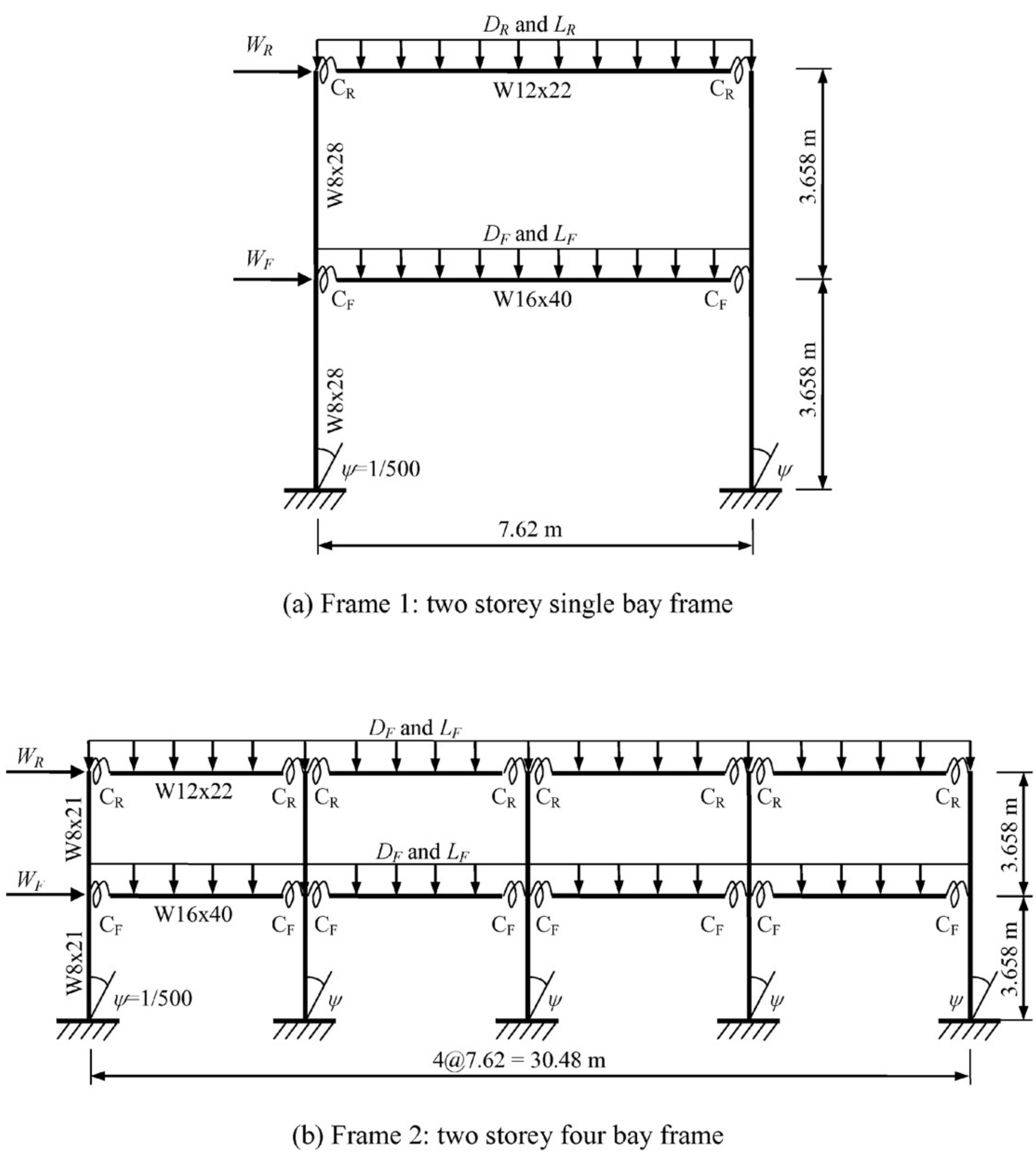


**Fig. 2.** Example semi-rigid frames designed by advanced analysis [38].