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On the modelling of initial geometric imperfections of steel frames in advanced analysis

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ABSTRACT

Steel structural members and frames always indicate imperfections to various degrees. These include initial out-of-straightness and initial out-of-plumb due to manufacturing and erection tolerances. In general, the shape and magnitude of geometric imperfections may have a significant influence on the response of a structure, and hence need to be modelled accurately when determining the load carrying capacity of a steel frame by advanced structural analysis. Most conveniently, geometric imperfections can be introduced in structural models as scaled eigenmodes obtained a priori from an elastic buckling analysis. However, it remains unanswered how many eigenmodes need to be incorporated and how to choose the scaling factors of each mode.

This paper presents a study of how the strength of steel frames varies with the number and magnitudes of eigenmodes. Frames with random geometric imperfections are produced using the statistics of measurements of out-of-plumb and member imperfections, and analysed using advanced geometric and material nonlinear analysis. The imperfections are then resolved into eigenmodes and a second set of advanced analysis is carried out using a finite number of modes to represent the imperfections. Conclusions are drawn about the appropriate number and magnitudes of eigenmodes to use in advanced structural analyses of steel frames.

1. Introduction

Steel structural members are not perfectly straight due to manufacturing and erection tolerances. In general, two types of initial geometrical imperfections should be taken into account in advanced (second-order inelastic) analysis: (i) the member out-of-straightness (bow imperfection) and (ii) the frame out-of-plumb (sway imperfection). In global frame analysis, the pattern of initial imperfections is often chosen to be the worst case scenario to maximize their destabilizing effects under the applied loads. Nevertheless, the worst case scenario of imperfections may be overly conservative. In reality, both initial out-of-straightness and initial out-of-plumb are random, and a rational modelling of geometric imperfections can only be achieved by using probabilistic methods. The modelling of geometric imperfections is much more complicated for a frame than for a single column because not only the magnitude but also the pattern (shape and the direction) of the imperfection affects the overall response of the frame. Although extensive research has been conducted on advanced analysis for steel structural systems [1,2], a rational method of modelling initial geometric imperfection in advanced analysis has yet to be developed.

There are a number of approaches to consider the effects of geometric imperfections in advanced analysis of steel frames. The common approaches include: scaling of elastic buckling mode (EBM), notional horizontal forces (NHF) method, reduction of member stiffness, and the direct modelling of initial geometric imperfections [3].

In the EBM method, a linear elastic buckling analysis of the perfect structure is first performed. The first buckling mode is then scaled to represent the imperfect geometry of the frame [4]. The assumption of the EBM method is that the first buckling mode represents the most critical imperfection geometry, which is similar to the deformation of the frame at collapse [5]. However, as a result of plastic deformations, the final failure mode of the frame may be different from the critical elastic buckling mode. An alternative approach was proposed by Alvarenga and Silveria [5] in which an inelastic second-order analysis is performed first to obtain the final collapse configuration, which is then used to model the imperfect geometry of the frame. This method, however, may be overly conservative. In the NHF method [6], artificial horizontal forces are introduced at each storey to account for the effect of frame out-of-plumb. This method is permitted in a number of steel specifications, e.g., AISC [7] and BS5950-1 [8]. For instance, AISC [7] stipulates the notional load as 0.2% of the gravity loads. Note that the value 0.2% is the maximum tolerance for out-of-plumb in steel structures as given in AISC [7]. The NHF method permits the use of straight elements in the structural model. The NHF method can also model imperfections of individual members by applying distributed lateral force along the

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member or a concentrated force at the middle of the member [3]. The degradation of member stiffness to model the effect of geometric imperfection was introduced by Kim [9]. In this method the elastic modulus *E* is reduced to 0.85*E* to account for geometric imperfections. The factor of 0.85 was determined by a calibration using plastic zone analyses and verified for a wide range of frames and columns. The model is applicable to both braced and unbraced frames with the same reduction factor of 0.85. This method has the advantage of eliminating the tedious work of explicit imperfection modelling or notional load application. However, the reduction factor 0.85 has not been verified by a probabilistic approach. Another approach is the direct modelling of initial geometric imperfections by offsetting the coordinates of the relevant nodes in the FE model from their original positions.

The main difficulty associated with most of the aforementioned methods is that no information is provided about the pattern of the imperfections. The designer has either to guess or consider many possible combinations to find the worst case scenario, a difficult task for a real structure. On the other hand, an incorrectly defined initial geometric imperfection may be beneficial to the system strength rather than being detrimental. In addition, the extension of these methods to three dimensional frame analysis is not straightforward.

The present study is concerned with developing a new method for modelling initial geometric imperfections in second-order inelastic analyses as a linear superposition of several scaled buckling modes. The statistical data of initial geometric imperfections are obtained in the literature and used in a probabilistic study to find a suitable number of buckling modes to be incorporated as well as the scaling factor for each buckling mode. For validation purposes, the performance of the proposed model is demonstrated by a number of case studies. The suggested procedure can be readily implemented into frame finite element analysis models and extended to 3D models.

2. Statistical data for initial geometric imperfections

The methods for modelling geometric imperfections can also be classified as deterministic or random. For deterministic modelling, the maximum amplitude of an initial geometric imperfection is typically determined from a steel structural specification. The pattern of the initial out-of-straightness is often assumed to be a half-sine wave and the frame out-of-plumb follows a linear pattern with all columns leaning in the same direction. In probabilistic modelling, the initial geometric imperfections (both shape and the magnitude) are treated as random variables. The probabilistic modelling requires statistical information for the geometric imperfections, such as distribution type, mean, and standard deviation. Ideally, the probabilistic models should be established on the basis of sufficient experimental data. This section summarises the statistical information for the geometric imperfections, which is needed in developing the proposed methods.

2.1. Initial out-of-straightness

Although a great number of experimental results on column strength can be found in the literature, very few studies report the detailed measurements of initial imperfections along the length of the member. In most studies, out-of-straightness is assumed to follow a half-sine shape and only the value at mid-span is reported which does not provide sufficient information about the contribution of higher order buckling modes with multiple half-waves. The statistical data for the out-of-straightness at mid-height of steel I-section members are summarised in Table 1. The presented results in this table show that a significant difference exists between measured imperfections from different regions. It appears that on average, Japanese sections have smaller initial out-of-straightness compared to those from Europe and North America.

Table 1
Statistical characteristics of initial out-of-straightness of hot-rolled I-sections in literature.

Mean (μ)	Standard deviation (σ)	Number of measurements	Reference
0.00160 (1/625)	0.000600	7	[20]
0.000204 (1/4910)	0.000160	9	[18]
0.00079 (1/1266)	0.000326	208	[19]
0.00050 (1/1996)	0.000433	437	[19]
0.00008 (1/12500)	0.000053	75	[21]
0.00025 (1/4000)	0.002000	350	[22]

In this study, both the shape and magnitude are treated as random variables. Thus, detailed measurements of initial imperfections along the length of the member are required to obtain the statistics of initial out-of-straightness. For a member in compression the buckling modes are assumed to take the form of sin $(i\pi x)$ where $i = 1, 2, 3, \ldots$ and $x \in [0, 1]$ is the non-dimensional coordinate along the length of the member (L) (see Fig. 1). In general, the initial out-of-straightness of the member can be expressed in terms of a linear combination of a given number of these buckling modes:

$$d_x = \Sigma_{i=1}^{m} a_i \sin(i\pi x) \quad x \in [0, 1] \tag{1}$$

in which d_x is the initial out-of-straightness at location x, a_i is the scale factor for the ith mode and m is the number of buckling modes included. In the following, it is assumed that a sample of N members is available and that for each member, the out-of straightness at m locations along the length of member is measured.

This study is based on the initial out-of-straightness measurements of nine IPE 160 columns carried out at the University of Politecnico di Milano [10] and published by ECCS Committee 8.1 [11]. Although the number of sample is limited (only 9), the reported data are very valuable as they give the geometric imperfection measurements at mid-point and also quarter points. As three readings of out-of-straightness are available for each sample, the out-of-straightness can be expressed as a linear combination of the first three buckling modes as shown in Fig. 1. The scale factors, or contributions of each mode (a_i, $i = 1, 2, 3$), can be determined by solving a set of three equations for each member (Eq. 1) and subsequently the statistical information of the scale factors a_1, a_2 and a_3 (mean and coefficient of variation (COV)) can be obtained. As shown in Table 1, the mean of the absolute values of measured out-of-straightness at mid-point, as reported in [11], is equal to 0.000204 (1/4910). This value appears to be very small compared to those reported in other similar studies, e.g., Fukumoto and Itoh [12]. Thus, while the COVs of the scale factors are based on these nine samples, the mean values are scaled up by a factor of 2.62 to match with the mean (1/1996) reported in [12], which is based on a much larger sample (437 measurements) of the initial out-of-straightness at the mid-span of the members. The scale factor of 2.62 was obtained based on the fact that if the first three buckling modes are used to model the initial

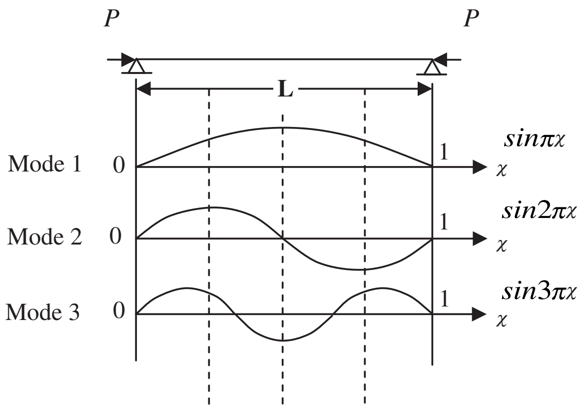

Fig. 1. First three buckling modes of simply supported axially loaded column.