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A simplified method to determine shear stiffness of thin walled cold formed steel storage rack frames

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ABSTRACT

The shear stiffness of braced frames of thin-walled cold-formed steel storage racks was experimentally and numerically investigated in order to establish the effect of connection flexibility on the accuracy of different analysis methods. The analyses which included a detailed 3D Finite Element model, a 2D frame analysis with beam elements and a simple hand calculation indicated significant variation of results compared with experimental values. A simplified modelling approach for 2D elastic analysis of braced frames was proposed. The approach is aimed at practical applications to account for the flexibility in bolted connections and leads to better approximation of the shear stiffness.

1. Introduction and background

Industrial steel storage racks are normally made from thin-walled cold-formed perforated sections carrying very heavy pallet loads. Due to their lightness and slenderness, they are very susceptible to horizontal actions and therefore, 2nd order effects and stability analyses are important design considerations for those structures. Industrial steel storage rack structures typically comprise of two orthogonal sets of vertical plane frames arranged parallel and perpendicular to the aisles. To resist lateral forces and to provide stiffness and stability, steel storage racks utilise moment resisting frames in the along aisle direction and use braced frames in the transverse direction crossing the aisle. Bracing members used in cross aisle directions are usually 'Lipped Channel' sections that are bolted to the upright perforations providing pin-end bracing connections, which may lead to translational softness due to bolt bending and the bearing effects between bolts and the uprights. Therefore, when carrying out a global analysis of the cross-aisle frames, experimental tests are used to obtain realistic values for the shear stiffness of a given type of braced frame.

Conducting laboratory experiments can be costly and is not always practical. In the absence of experimental values, analyses that approximate real shear stiffness can have varying levels of accuracy and range from detailed 3D or 2D Finite Element simulations to simple hand calculations for a given type of braced frame. This paper compares the accuracy of different analysis methods with test results and proposes a simple analytical approach to approximate the connection flexibility in cross-aisle frames. The proposed method leads to stiffness correction factors, which can be incorporated in an elastic analysis to obtain better values for the shear stiffness of the entire frame.

A well-known hand calculation method is Timoshenko's theoretical equation for deriving shear stiffness of built-up columns [1]. Timoshenko's theoretical equation, which considers the width-depth aspect ratio of the bracing panel and the cross-section properties of the bracing members, can be safely adopted for hot rolled structures in which the joint flexibilities are negligible. However, for thin-walled cold-formed structures used for storage racks, the mentioned method may lead to unrealistic outcomes. RMI [2] and AS4084 [3] accept Timoshenko's theoretical formula to calculate the elastic buckling load "P_{cr}" for upright frames braced with diagonals when the connection flexibility is negligible. Few investigations have been reported on the shear stiffness of steel storage rack upright frames consisting of thin-walled cold-formed steel profiles and bolted connections. Rao et al. [4] and Sajja et al. [5,6] carried out numerical and experimental investigations on the shear stiffness of rack upright frames using various number of panels, aspect ratios, upright sizes, restraints and bracing configurations. Rao et al. [4] examined the inaccuracy of RMI specifications in the design of cross aisle braced frames by conducting an extensive experimental program including frames with different aspect ratios and

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different bracing arrangement. They concluded that Timoshenko and Gere' [1] theory can overestimate the shear stiffness by a factor up to 20. Furthermore, their linear numerical models were not able to accurately match the experimental results.

BS EN 15512 [7] explains, in detail the test set-up and how to conduct experimental tests to determine the longitudinal shear stiffness of upright frames (Fig. 1). This test set up was originally recommended by Sajja et al. [5] to improve the old test method based on European Standard (FEM-2008) [8]. Australian Standard AS4084 [3] has been also updated by Gilbert and Rasmussen [9] who proposed an alternative test set up, shown in Fig. 2, to account for both bending and shear effects. Experimental testing is a reliable method for determining the shear stiffness of low to mid-rise industrial steel storage rack structures but, as mentioned earlier, it can be time consuming and expensive and therefore there is a need for a practical method to determine the transverse shear stiffness of braced cold-formed thin-walled frames used in storage racks. In the remaining part of this paper, two sets of experimental shear stiffness values are presented in comparison with results obtained from finite element simulations and from Timoshenko's standard based approach. Finally, a simple method to better account for the connection flexibility is proposed and its effectiveness is compared with other approaches.

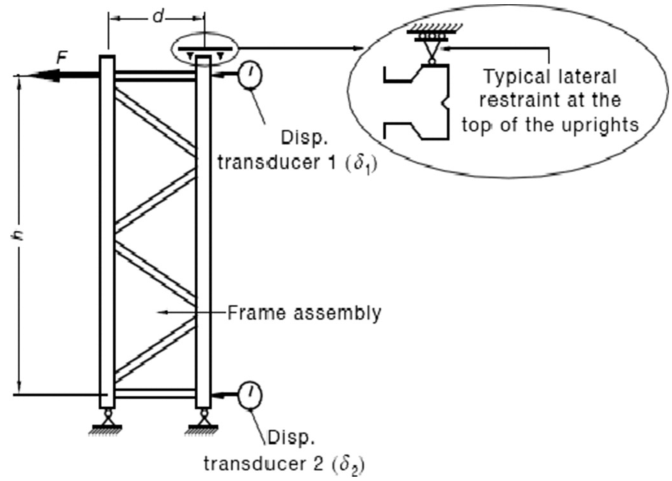

Fig. 2. Test set up for measuring the combined shear and bending stiffness of upright frames [3].

2. Experimental investigations

In this study, two types of upright frames, referred to in this paper as Type A and Type B, have been tested in order to establish their shear stiffness values. The difference between the two types of upright frames is the section properties of the upright members. Type B upright members are stiffer and larger in size compared with Type A uprights. A total number of six tests on upright frames, three frames for each type, have been considered in this study. The test setup, shown in Fig. 4, was based on the Australian Standard AS4084-2012 [3] as depicted in Fig. 3, whereby the distance (d) between uprights has been measured from the front faces of the uprights. Each upright frame was placed in the test rig with its plane in a horizontal orientation. In the out-of-plane (vertical) direction, the frame was supported on skates that allowed the uprights to slide freely along their axes. To prevent the frame from rotating or moving in the horizontal plane, the end of one upright was pinned (point A) while the diagonally opposite end (point B) of the other upright was roller supported. During the test, a compressive force (*F*) was applied at point B by means of a hydraulic jack along the centroid axis of the upright and the corresponding relative displacement between the uprights (δ) was determined. The required data was recorded using one load cell placed at point B between the jack and the upright, while two Linear Variable Displacement Transducers (LVDTs) were used to measure the displacements at points B and A along the axes of the uprights. The relative displacement (δ) was taken conservatively as the difference between the LVDT readings at A and B. During the test, the load was increased until a linear portion of the load deformation curve could be established and later used to derive the shear stiffness of the frame. The loads applied to the specimen were further increased until failure of the frame was reached. To prevent out-of-plane warping of the frames, as the load was increased, two further skates were placed above the upright flanges at the free ends at points C and D. Observed causes of failure were consistently the bending of the bolts followed by tearing of bolthole of one of the bracing members in the Type A frames, as depicted in Fig. 5, while in the Type B frames the failure was due to the shearing of one of the bracing bolts. Force-Displacement curves obtained from tests on Type A uprights are shown in Fig. 6. In Fig. 6, a best-fit straight line for the linear portion of each experimental curve, identified by two points, was used to approximate the slope and hence the frame's stiffness k_{ti} in the longitudinal direction. The stiffness values k_{ti} obtained from the tests for Type A and Type B upright frames, respectively, are summarised in Tables 1 and 2. The averaged shear stiffness values for Type A and B upright frames are 3.46 kN/mm and 5.31 kN/mm, respectively.

3. Numerical investigations

To compare the accuracy of different analysis approaches with test results, three numerical models are considered. The first analysis approach involves a 3D Finite Element model incorporating both geometric and material non-linearity with the aim of simulating the structural response of the frame as accurately as possible. Considering that such FE modelling can be time consuming and not always practical, a conventional 2D elastic frame analysis model, which would be familiar to most practicing engineers, was developed using the SAP 2000 program. Similar to what has been reported by Rao et al. [4] and Gilbert et al. [9], the results of the linear analysis and the experiment were found to be vastly different and therefore, as will be presented later in this paper, stiffness correction factors for the bracing members were developed

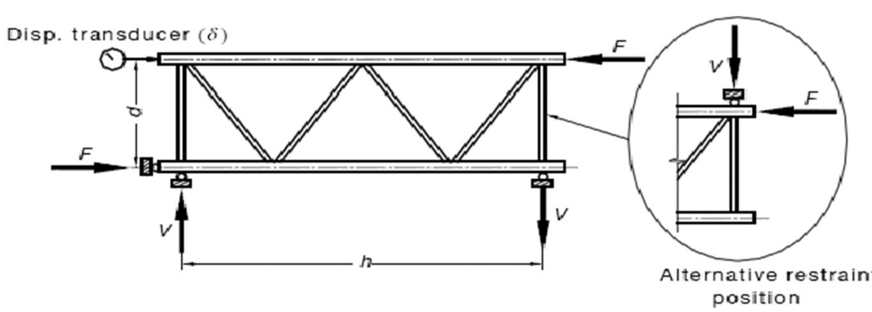

Fig. 1. Upright frame test set up for measuring the shear stiffness of upright frames [7].