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Direct stiffness model of slant connection under thermal and non-symmetric gravity load

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ABSTRACT

Conventional steel beams exhibit lower structural performance when subjected to thermally induced axial expansion. In this regard, the design of a connection plays an utmost essential role in restrained beams. Most existing studies on the thermal behaviour of connections have so far focused only on vertical end-plate (conventional) type. This paper describes therefore the elastic mechanical behaviour of a newly proposed beam with a slant bolted end-plate connection under non-symmetric gravity load in the presence of an elevated temperature by means of direct stiffness finite element modelling. The presented direct stiffness method is relatively easy and useful to evaluate the behaviour of a steel beam with slant end-plate connection of various dimensions due to temperature increase. The performance of slant end-plate connections, with a proposed capability of damping additional thermally induced axial force, is determined under two resisting mechanisms. First, by friction force dissipation between two faces of slant end-plate connection and second, by small upward crawling on inclined plane. The applicability of the current model is ensured through a satisfactory verification with the results from the experimental test. Departing from the good agreement, a series of design charts in terms of axial force and temperature that initiates end-plate crawling has been produced for various friction factors and slanting angles.

1. Introduction

The exploration for an inexpensive resistance method to improve the performance of steel structures due to thermal effects persists to be a demanding task that captures the attention of structural engineers in recent decades. In steel structures, designers are obliged to get an optimized solution to handle thermal effects for axially restrained beams. A number of common solutions are: (i) increase in section area, (ii) using side supports [1], (iii) cooling method by air-conditioning and water [2], (iv) jacketing method by concrete or isolation [3,4], and (v) thermal break [5]. However, most of these existing methods are extensively costly.

In the search for superior thermal resistance method, supports and member's behaviours at elevated temperature remain the main subject of study in numerous researches exploring on various structural issues. Rodrigues et al. [6] found by experimental means that the thermal failure in steel structures occurs in two important phases: elastic and inelastic. However, in several cases, the first phase is due to the initiation of failure that passes the tangential elastic modulus [7,8]. Mourão and Silva [9] showed that the elongation of beams due to temperature rise is one of the primary causes of elastic failure. Yin and Wang [10] explored the impact of thermal expansion by analysing an axially restrained beam by means of numerical method. Simoes da Silva et al. [11] showed that the feature of connections plays a vital role in bearing or damping thermal expansion of an axially restrained beam in steel structures. Heidarpour and Bradford [12] certified that the stiffness and rigidity of connections are directly dependent on the amount of axial force in the beam. Kalogeropoulos et al. [13] and Al-Jabri [14] simulated numerically the response of connections at elevated temperature for logical compression and tension stiffness at connection zone for various cases to validate experimental work by Qian et al. [15]. For seismic load resistance, Della Corte et al. [16,17] and Mazzolani et al. [18] examined the inelastic response of shear links with axial restraints of bolted end-plate connection used in eccentric bracing of steel and reinforced concrete structures, due to appreciably enhanced lateral stiffness and ductility. Such plastic shear over-strength is attributed to axial force acting on the links, the ratio of link flange to web area, and the ratio of link length to cross-sectional depth. In particular, additional tensile axial forces were observed under the influence of axial restraints and nonlinear geometric effects, affecting the system ductility as a whole. It is

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notable to mention that most studies in steel beams have only focused on commonly used structural reactions due to thermally induced axial forces [19,20]. Up to now, there is no structurally trustworthy suggestion to control and reduce the thermal axial force within the restrained beams.

In the current work, we therefore further explore the slanted end-plate connections as the proposed structural solution to inhibit beam and connections from an early thermally induced failure by means of direct stiffness method. The fundamental development of an analytical model of such a connection when subjected to a non-symmetric gravity load and a temperature rise has been readily formulated by Zahmatkesh et al. [21]. It was found that an increase in temperature in the beam with a conventional connection induces an additional axial force that reduces the ability in bearing external gravity loads. Also, the study proved that by changing the connection to that of slanting type, the additional axial force can be dissipated more efficiently. In the spirit of this analytical modelling, a 1D direct stiffness finite element method is presented to derive the equilibrium equations for beams with a slant end-plate connection in the presence of an elevated temperature when subjected to non-symmetric gravity load in the elastic domain.

2. Vertical and slant end-plate connection characteristics of beam subjected to temperature increase

2.1. Vertical and slant end-plate connections

Figs. 1 and 2 illustrate the configurations of a vertical end-plate and a real scale slant end-plate connections, respectively. The popularity of bolted end-plate connections is largely due to its simplicity in fabrication and installation. In general, these connections consist of end-plates that are welded to the ends of a beam in the workshop and then bolted to the flange of columns on site. They are usually used in industrial structures, knee connections of residential towers as well as end-plate and beam connections of gable roofs. The maximum angle of slanting end-plate connection (Fig. 2) is practically limited to 60° [21]. A higher angle is not practical due to inconvenience of fitting the bolts into the holes at the top and bottom of end-plate. For both vertical and slant end-plate connections, there exist gap tolerances for the bolt and hole designated for bolt fixing. In slant end-plate connection, the gap plays an important function, i.e., to allow a small movement of the beam's end when it is subjected to thermal expansion.

2.2. Damping of thermal force in beams

A beam with restrained supports tends to have an expansion when it is subjected to temperature rise. So, if the supports are fixed and inflexible for motion allowance, their reactions will apply huge axial force into the beam. The elongation of members in the elastic regime of material is mostly very small. Therefore, the introduction of the slant end-plate connection can damp the existing axial force by allowing the ends of beam to crawl on the connection surface due to elongation of the beam. The movement is made possible due to the existence of a gap clearance for the bolt in the hole. Hypotheses about the stages of the performance and the reaction of end-plate connections due to increase in temperature are shown in Figs. 3 and 4, for vertical and slant types, respectively. It is assumed that, after an increase in temperature, thermal force is generated in the beam, P_t. The beam generally tends to reach buckling load (P_{cr}) due to an increase in axial force, because the vertical end-plate connection does not allow the beam to have expansion (Fig. 3). Although there is a vertical motion tolerance between the surfaces in vertical end-plate connections, it is unable to absorb the expansion of the two ends of the beam in horizontal direction because the direction of expansion is perpendicular to the direction of moving surface.

On the other hand, in the slant end-plate connection, the slant surface allows the beam to damp the axial force by means of linear crawling on the slant surface (Fig. 4). In the slant end-plate connection, there is a slanting tolerance between the surfaces such that it can absorb the expansion of the two ends of the beam using crawling mechanism over the slanting faces, because the direction of horizontal expansion can be propelled to the slanting plane of connection.

3. Direct stiffness finite element formulation

3.1. Case study description

In practice, the applied gravity load is mostly not symmetric and uniform, such as wall load at the mid span of the beam. So, it is obligatory to consider the effects of non-symmetric gravity load on the beam. In the current formulation, three case studies are simulated in two common categories; before thermal effect and after uniform elevated temperature. In the first case study, it is assumed that the two ends of the beam are supported with rollers on a fixed slanting plane that can carry the moment. The second case study is similar to the first one, but its difference is that there exists a friction force between the two end-plates. In the third case study, friction bolts are used instead of the normal bolts. The effects of various types of

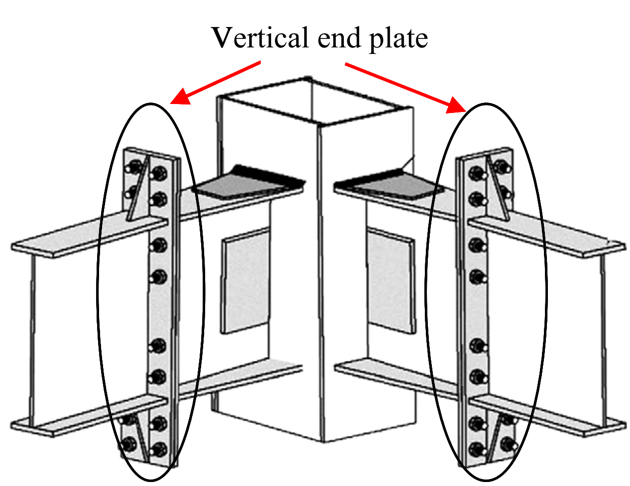

Fig. 1. Steel vertical bolted end-plate connections.