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Nonlinear response of bolt groups under in-plane loading

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Abstract

The use of bolted joints to connect structural members together and to transfer in-plane forces between them has been extensively employed in civil, mechanical and aeronautic structures. Most of the available methods have been developed to estimate the loading capacity but not the deformation of bolt groups. In this paper, an iterative procedure is developed to calculate the non-linear deformation of bolt groups under in-plane eccentric loads based on the assumptions of elasto-plastic behaviour of bolts and rigid body movement of the bolt group. The force exerted on each bolt is proposed to be dependent on the instantaneous centre of rotation of the bolt group. A computer program based on the above theory has been implemented to simulate the full range non-linear response of bolt groups subjected to in-plane loads, in particular, the load–slip behaviour at the inelastic range. A numerical example is given, with comparison to the non-linear finite element analysis, to illustrate the effectiveness and accuracy of the method. The behaviour of a bolt group as well as individual bolts subjected to in-plane loads was studied in detail. It was found that the ultimate capacity of the bolt group could be about 30% higher than its elastic limit. A ductility factor of 3 to 4 might be required for the bolts in a bolt group to reach their ultimate loading capacity.

Keywords: Non-linear; Bolt group; In-plane loading; Elastic; Plastic; Slip; Centre of rotation

1. Introduction

The use of bolted joints to connect structural members together and to transfer in-plane forces between them has been extensively employed in civil, mechanical and aeronautic structures [1–3]. Many studies have been carried out to estimate the ultimate capacity of bolted joints in resisting eccentric in-plane loads for steel structures [4–12]. The classic approach [4] assumed all the bolts are fitted perfectly and deform only in an elastic manner. By such assumptions, the loads carried by the bolts in a bolt group at the elastic limit could be easily obtained. Alternatively, all the bolts could be assumed to be fully plastic and the ultimate load-carrying capacity of bolt groups was then evaluated [5]. Crawford and Kulak [8] proposed the ultimate strength method, which assumed that all bolts rotate about a certain instantaneous centre of rotation and the non-linear behaviour of individual bolts was taken into account. By considering equilibrium of the bolt group, the instantaneous centre of rotation and the ultimate strength of the connection could be found by an iterative approach. Surtees et al. [9] combined elastic and plastic analyses and proposed an elasto-plastic analysis, which postulated the behaviour of any bolt as being either elastic or plastic, and was governed by the distance of the bolts from the instantaneous centre of rotation of the connection. An alternative approach assuming the in-plane load was distributed in proportion to the available bearing area instead of the shear area was suggested for aluminium structures [13]. The aforementioned approaches are useful for estimating the strength but not the deformation of bolt groups.

While the major application of the bolt group analysis is on steelwork connections, the analysis can also be applied to anchor bolt groups subjected to in-plane eccentric loadings like reinforced concrete beams strengthened with steel plates at their sides [3,14–16]. It was pointed out [14–16] that not only the load-carrying capacity but also the load–slip relationship of bolts could significantly affect the load-carrying capacity of the beams strengthened with externally bolted steel plates. The importance in controlling the slip of anchor bolts was confirmed by an experimental study [3] of retrofitted concrete coupling beams by bolted side plate. Although load–slip relationships of individual bolts and bolt groups are so important in

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retrofitting, no theory has yet been proposed to calculate the non-linear deformation of bolted connections under external loads. Complicated non-linear finite element analysis appears to be the only means to simulate the complete load deformation relationship of bolt groups.

The objective of the present study is to develop an original iterative procedure to compute the non-linear load–deformation relationship of bolt groups, which consist of un-yielded and yielded bolts, under any in-plane external load. Apart from the normal assumptions used in elastic analysis of bolt groups, it is further postulated that the direction of force of the yielded bolts depends on the centre of rotation of the bolt group. By varying the centre of rotation, equilibrium between yielded bolt forces and applied loads could be sought in each loading step. For simplicity, the load–slip behaviour of individual bolts is idealized as a bi-linear relationship, which was commonly adopted in other similar studies [3,9,17]. An original computer program has been implemented to illustrate and validate the procedure.

Compared with the other available techniques, the new procedure offers several advantages. Firstly, the deformation of bolt groups in any geometry subjected to any in-plane load can be predicted. Secondly, the gradual shift of the instantaneous centre of rotation of bolt groups can be taken into account, improving its accuracy in the ultimate strength estimation. Finally, the limited slip capacity of bolts, which being difficult to be defined in finite element analyses, is considered in the calculation of the load–deformation response of bolt groups.

2. Non-linear theory on bolt groups

Detailed theory relating the applied loading and the corresponding deformation of a bolt group consisting of yielded and un-yielded bolts is established in this section. The theory can be applied to trace the complete load–deformation of bolt groups under eccentric in-plane loading.

2.1. Basic assumptions

The basic assumptions adopted in the development of the theory include:

(1) The bolts are perfectly fitted and connected by a plate, which acts as if rigid [4,13].
(2) The bolts deform in an elasto-plastic manner.
(3) The bolts are widely separated such that the interference between bolts can be neglected.

The first assumption idealizes the bolts as being perfectly fitted in the connection media. In practice, a clearance hole is often used to facilitate the installation of bolts, making the bolts not perfectly fitted and affecting the load deformation responses of bolts [6,7]. However, the influence is usually small and diminishes as more bolts are in close contact with the connection media through slips. So it is acceptable to ignore the above effect and the bolts may be assumed as perfectly fitted. However, when the bolt slips have to be limited, high strength friction grip bolts and dynamic set anchors (a proprietary technology of Hilti Company) may be used for steel and concrete structures, respectively, to control the undesirable slips. Moreover, based on the first assumption, only rigid body motion is admissible for the bolt group. As a result, the relative positions of all the bolts remain unchanged after deformation. It implies that bolts rotate about a point which is known as the instantaneous centre of rotation.

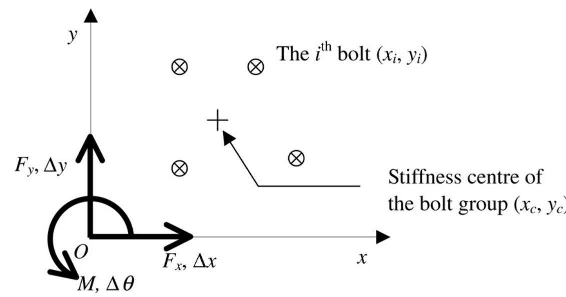

Fig. 1. General arrangement of bolt group.

The second assumption is an extension of the elastic assumption in classic bolt group theory. In elastic analysis, it is assumed that bolts behave elastically until reaching the yield stress. This assumption is extended to the post-yield stage that the magnitude of the bolt force remains the same i.e. plastic stage. In reality, a clear yield point does not exist and the stiffness of the bolt drops gradually until failure [6,8]. However, the elasto-plastic assumption of bolts has been widely accepted for different engineering applications, including bolt group analysis [7,9] because of its simplicity and readiness to be analyzed in different circumstances. While the magnitude of bolt force is assumed to remain unchanged in the post-yield stage, it is further postulated that the direction of the yielded bolt force varies according to the incremental displacement. As the bolt group is assumed to displace in a rigid body manner, the bolt force of any yielded bolt would be perpendicular to the line joining the instantaneous centre of rotation (x_o, y_o) and the location of that bolt as shown in Fig. 3.

Furthermore, according to the first and third assumptions, the force exerted on each bolt can be readily obtained from the deformation of the bolt. After calculation of the polar moment of inertia and the stiffness of the bolt group, the relationship between the rigid body movement of the bolt group and the in-plane eccentric loads can be established.

2.2. Classic elastic theory on bolt groups

For completeness, the classic elastic theory [4] for analyzing bolt groups subjected to in-plane loads is reviewed. Based on that, the newly developed non-linear bolt group theory will be presented in the next section.

Fig. 1 shows a general arrangement of a group of bolts subjected to general external loads (F_x, F_y, M). The lateral stiffness of the ith bolt in the x and y directions are k_{xi} and k_{yi} respectively. The lateral movements of the bolt group at the origin of the coordinate system are denoted by (Δx, Δy, $\Delta\theta$). Based on the first assumption, the lateral movements of the ith