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Mechanical modeling of bolted T-stub connections under cyclic loads Part I: Stiffness Modeling

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ABSTRACT

This paper deals with mechanical models which make it possible to reliably simulate the complete moment–rotation curves in the full-scale T-stub connections subjected to cyclic loads. The behavior of these bolted connections becomes complex because the various response mechanisms of individual connection components interact with one another and have influence on the overall rotational stiffness of the connection. Accordingly, the mechanical joint models are made up of individual T-stub components modeled as nonlinear springs. The behaviors of component members including tension bolt uplift, bending of the T-stub flange, elongation of the T-stem, relative slip deformation, and bearing deformation are reproduced by the multi-nonlinear stiffness models obtained from their force-deformation response mechanisms. These stiffness properties should be assigned into the component springs implemented into the joint element so as to numerically generate the behavior of full-scale connections with considerable accuracy. Thus, this part (Part I) intends to focus on describing the stiffness models, which are based on the basic component spring theory, in an effort to provide insight into the behavior, failure modes, and ductility of T-stub components in the connection.

1. Introduction

The behavior of full-scale connections typically represented by a nonlinear moment–rotation curve is based on the various response mechanisms of individual connection components [1–5]. The behavior of each connection component under monotonic loads is fairly simple to simulate with bi-linear or tri-linear stiffness expressions. However, the interaction between connection components is not always easy to predict because they are not behaving independently anymore within the connection. Moreover, this problem is compounded for the case of large cyclic deformations where careful checking on permanent deformations is needed [6]. Therefore, the connection models are very complex and require a large number of stiffness components. For the computational convenience, structural connections designed in the past were assumed to be extreme behavioral ones, i.e., the simple pinned connections and the ideally welded connections, and therefore the necessity for the actual moment–rotation response of the connection was very limited [7,8]. In reality, most connections including bolted connections exhibit the intermediate behavior between two extreme cases.

The mechanical modeling of steel bolted connections is based on the characterization of individual component members, with a well defined behavior inside the connection [9,10]. The connection components need to schematize the deformability contributions so as to take their interaction into consideration. They can be modeled as the nonlinear component springs with their own stiffness properties. Therefore, mechanical models, which are formed as an assembly of component springs and rigid elements, are suitable for the simulation of complex connection behavior under either static or dynamic loads.

This modeling approach provides the flexibility which is able to accommodate different connection configurations with the same basic component spring theory [10,11]. In this case, the connection can be decomposed into the proper component springs, and then their individual responses are assembled to reproduce the behavior of the full-scale connection. It has the clear advantage of being easily scalable to the modeling of bolted connections. In addition, the mechanical models can relieve high computational complexity and cost in comparison with exiting finite element (FE) models commonly used for calibration. For these advantages, the mechanical modeling has been accepted for the reliable estimation of their nonlinear response. The mechanical models in the established researches [10–14] lay more focus on predicting the initial stiffness and ultimate strength rather than the entire moment–rotation curve, especially, the rotational capacity. Therefore, the mechanical models, which are able to simulate the complete moment–rotation curve of full-scale bolted connections, will be dealt with under cyclic loads.

In this part (Part I), the stiffness models determined by the cyclic deformation responses of T-stub connection components are mainly

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presented. The stiffness model predictions of T-stub connection components with respect to initial stiffness, ultimate capacity, and dominant failure mode are built into the multi-linear models for each force-deformation mechanism. The contributions of deformability mechanisms between T-stub component members are also investigated by first quantifying their force-deformation responses in the connection. These response mechanisms for individual connection components are then combined in parallel or in series according to the interaction of the force transfer. Finally, the component springs with the combined response mechanism are installed on a joint model in order to accurately simulate the moment–rotation curve of structural connections apart from experimental testing. A series of these tasks are required prior to the development of the mechanical joint model described in the companion paper (Part II) [15].

2. Mechanical joint model

The mechanical spring model initially introduced by the Eurocode 3 [11] provides an efficient solution for obtaining either continuous or multi-linear moment–rotation curves, as compared with currently existing methods: (1) experimental testing; (2) refined FE modeling; and (3) analytical curve fitting model. In this mechanical model, the individual components of the connection are converted into the component springs. The behavior of these springs can be controlled by the stiffness model which simplifies the actual force-deformation response of connection components. In an effort to properly apply the behavior of bolted T-stub connections to the mechanical modeling, each of component springs should be added to the system in accordance with the force transfer from beam to connection. After considering the modeling philosophy for this spring assemblage, the overall rotational stiffness of the connection is affected by the combined stiffness models.

Fig. 1(a) and (b) show the idealization of the force distribution at the T-stub connection and the installation of idealized nonlinear springs in the mechanical joint model, respectively. Generally, the beam develops its flexural strength (i.e. plastic hinge) and carries the bending moment (M) transformed from the total applied force (T) at the tip of the beam. This bending moment is transmitted to the connection as the converted axial forces (P). The internal reactions in the connection component act against these external forces in order to satisfy equilibrium. They have the following relationship as shown in Fig. 1(a):

$$M_r = M_P + Tx = TL \tag{1}$$

$$M_r = \Sigma B_{n1} H_{B1} + \Sigma B_{n2} H_{B2} - Q_1 H_{Q1} - Q_2 H_{Q2} \tag{2}$$

$$P = \frac{M_r}{d} \tag{3}$$

$$P = \Sigma B_{n1} + \Sigma B_{n2} - Q_1 - Q_2 \tag{4a}$$

$$P = \Sigma R_b \tag{4b}$$

where M_r is the internal resistant moment; M_P is the plastic moment; x is the distance from the column surface to the position of the plastic hinge; L is the length of the beam; H_{B1}, H_{B2}, H_{Q1}, H_{Q2}, and H_{Q2} are the equivalent heights at each position shown in Fig. 1(a); ΣB_{n1} and ΣB_{n2} are the summation of bolt reaction forces in tension; Q_1 and Q_2 are the prying force acting on the tip of the T-stub flange due to the initial bolt pretension; d denotes the depth of the beam; and ΣR_b represents the bearing force in compression. As shown in Eqs. (4a) and (4b), the force equilibriums are established under tension and compression.

Mechanisms that have an effect on the behavior of T-stub connections are classified by five main deformation responses: (1) overall T-stub deformation; (2) panel zone deformation; (3) beam deformation including plastic hinges; (4) shear deformation within the connected region; and (5) shear tab deformation. The mechanical joint model shown in Fig. 1(b) can reflect these mechanisms very well on the ground that the internal loads are carried by the component springs corresponding to the component members. The response of the panel zone under the shear deformations resulting from the bending forces occurs at the panel zone spring. It is deformed in a scissors-line manner. In particular, the end face of the beam modeled as the rigid element is assumed to behave as a rigid plate, leading to a linear strain pivoting about the center of bearing.

The combined component springs for the T-stub component are attached between the panel zone and the rigid element (Fig. 1(b)). They deform directly by the converted axial forces (P). Their mechanisms are very complex and incorporate various types of deformation. The behavior of the T-stub component as well as the shear deformation of the panel zone has a significant effect on the moment-rotation curve. Thus, in spite of difficulty in modeling, both mechanisms are investigated in this study because of this reason.

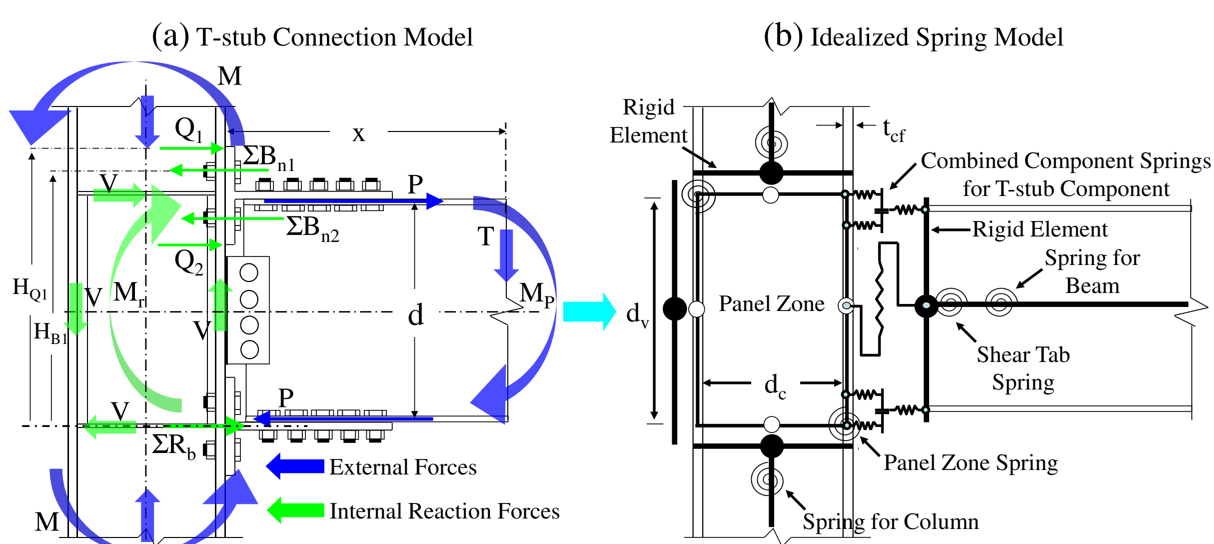

Fig. 1. Spring model for the full-scale T-stub connection.