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Use of artificial damping factors to enhance numerical stability for irregular joints

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ABSTRACT

The authors previously proposed a fast and easy assembly method for wide flange steel column-beam frames in which the column and beam steel web had skew cuts and the lower flange of the steel beam was partially removed to prevent the bottom flange of the steel beam from running into the flanges of the L-shaped guide angles (which were pre-installed on the column bracket) when they were erected. However, the joint experienced convergence difficulties at the irregular structural configuration of the skewed web connections when cyclic finite element analysis was performed. This study introduced artificial damping factors, implemented during nonlinear numerical computation, to balance the internal and external forces. The influence of the damping factors was explored to ameliorate the numerical instabilities by removing the aforementioned convergence difficulties. It was shown that a solution converged while the dissipated stabilization energy was sufficiently small, ensuring that the analysis results were not distorted by the use of damping factors in the range of 1.0×10^{-5} to 5.0×10^{-5}. The best matches with monotonic runs and the convergence for steels with yield strength of 325 MPa were obtained by applying damping factors of 0.0002 and 0.0005.

1. Introduction; previous studies and significance of this study

Extensive analytical and experimental investigations have been carried out in attempts to understand the structural behavior of steel beam-column joints subjected to either monotonic or cyclic loads [2, 4, 5, 13]. Using a nonlinear finite element package, Muresan and Balc [9] investigated the behavior of beam-to-column joints. In their study, all elements in the tension region of the joint were modeled with equivalent T-stubs. It was found that the joint exhibited increased deformation around its tension flange. In addition, the issues and challenges facing numerical simulations of steel bolted joints were also reported [3]. It was concluded that the analysis of bolted joints depends mainly on the following variables: constitutive relations, step size, element type, number of integration points in the elements, kinematic descriptions, and discretization. These elements demonstrated nonlinear behavior, which required more attention when dealing with finite element analysis. Accordingly, previous researchers established simplified methods for bolt modeling. Due to their relative economy and more rapid construction, prefabricated structural members were gaining popularity in the construction industry [6, 10, 11, 14]. In earlier study, the authors proposed an irregular structural configuration of the skewed web connection for fast and easy assemble of steel frames. A 3D nonlinear finite element model representing the proposed joint was performed to better understand the structural behavior of the joint. However, the convergence difficulties have occurred at the irregular skewed web, and the numerical instability increased in an unbounded manner when the viscosity and nonlinearity in the numerical solution process were neglected. In many engineering fields, the artificial damping terms (ADT) were used in solving problems including aeroacoustics, wave and fluid flow problems. Sun et al. [12] developed methods to facilitate stable and accurate numerical solutions of linearized Euler equations, which were often used in solving problems in computational aeroacoustics. In their works, two new methods that used artificial damping terms (ADT) were introduced. One of their methods was constructed to damp the vortical components generated during the computation. An artificial damping algorithm for solving the Helmholtz problem was also considered by Kim and Lee [7]. When the imaginary part of the wave number was small, the problem was known to be difficult to solve. In their paper, an efficient artificial damping algorithm which can be viewed as a rational iteration was proposed. Each damped problem was solved incompletely by a nonoverlapping domain decomposition method. Liu and Nithiarasu [8] modeled the upper-convected Maxwell (UCM). In addition to allowing equal-order interpolations for pressure and velocity, they proposed method along with an appropriate artificial damping scheme which was able to produce stable solutions for different Deborah numbers (*De*). They showed that an additional damping was essential to maintain positive definitiveness of the conformation tensor at higher *De*. They also demonstrated the need for an additional damping by

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analyzing the basic forward time central space scheme applied to the constitutive equations.

To overcome these convergence problems and to suppress the growth of instabilities observed in the proposed irregular joints in the present study, the artificial damping factors were used during nonlinear numerical computation in order to balance the internal and external forces for cyclic load applications. At all nodes, the equilibrium state with added damping factors was found without distorting the analysis results which was compared with the numerical solutions obtained with monolithic loads. Finally, sensitivity analysis of the damping factors was conducted to investigate their influences on the structural behavior of the proposed joint.

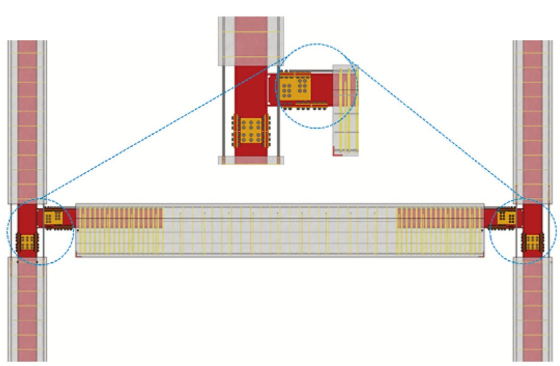
2. Numerical evaluation of the proposed connections

2.1. Instabilities in the model with irregular cuts

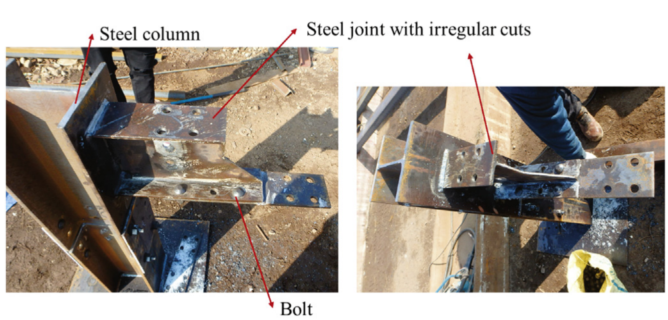
In this study, a fast and easy assembly method was proposed for column-beam frames having wide flange steels, in which the column and beam steel web had skew cuts being placed in the L-shaped guide angles until permanent connections were made by bolting stiffener plates to obtain a double shear connection. The conventional erection of heavy frames with heavy stiffeners and multiple bolts was replaced by the erection with novel connections having skew cuts along the column and beam steel web. The lower flange of the steel column bracket and beam was also partially removed to prevent the bottom flange of the steel beam from running into the flanges of the L-shaped guide angles (which were pre-installed on the column bracket). These helped the bottom flange of the steel beam to be placed into L-shaped angles, which were pre-installed on the column bracket, when they were erected. This assembly method was proposed for use in the steel construction industry; however, it can also be extended to precast frames, helping to erect and assemble heavy precast frames. Steel frames encased in precast concrete shown in Fig. 1 were proposed to provide efficient structural resistance to heavy floor loadings over 20 kN/m^2.

Numerical analysis based on cyclic analysis of the connection was performed to evaluate the cyclic hysteretic behavior of the proposed connections with L-shaped guide angles in order to verify the structural stability of the proposed connection. Particular attention was paid to the influence of the irregular web cuts on the flexural capacity of the joints. The finite element meshes of the web joint with the skew cut, constructed for the proposed connections, and the L-type guide angles and stiffener plate are shown in Figs. 2 and 3. CD8R elements are utilized for the steel, stiffeners, and bolts. Table 1 presents the material properties used in the numerical analysis of the proposed joint. Steel sections with a tensile yield stress (F_y) of 325 MPa and high-strength bolts with a tensile yield stress of 900 MPa were used in the numerical study. A 3D FE model of the proposed joint was discretized using the ABAQUS modeling tool [1]. Two types of elements (C3D8R and R3D4) were chosen to represent the joint connection. Elements of type C3D8R, which are referred to as reduced integration elements, were preferred because they were suitable for nonlinear static analysis. In addition, these elements demonstrated similar behavior to that of C3D8 elements, with the exception that the eight integration points were reduced to a single integration point, decreasing the required running time. These elements (C3D8R) are applied in the ABAQUS model, as illustrated in Fig. 3. Alternatively, elements of type R3D4 are used to model a rigid body, as shown in Fig. 3. The rigid body was used in this analysis to locate the reference point at which a cyclic load was exerted. Two constrained areas (i.e., fixed conditions), as shown in Fig. 3, are defined at both ends of the steel column in order to restrain the movement of the model during the application of cyclic loads.

In Fig. 4, numerical errors were identified at nodes #1 and #2 in the neighborhood of the sharp edges, which prematurely terminated the numerical computation for the cyclic moment-displacement relationship as represented by Legend 3 (refer to Fig. 6) at a stroke around 60 mm. The irregularities of structural configuration such as sharp edges may cause convergence difficulties and numerical instability to some degree. The residual force (R_b) shown in Fig. 5 failed to balance the internal and external forces. As the analysis proceeded, the cyclic analysis did not converge, as indicated by the residual force, R_b, which failed to balance the internal and external forces, as shown in Fig. 5. The influence of the damping factor on the analysis results and convergence is shown in Fig. 6, where the computation represented by Legend 3 was terminated at a stroke around 60 mm without a damping factor. The numerical instabilities were resolved by introducing an artificial damping factor, where a default damping factor was used to overcome the numerical instability, and obtain cyclic moment-displacement relationship as represented by Legend 4. However, the flexural strength with artificial damping factor of 0.0002 was over-estimated compared with that calculated monotonically.



(a) Precast steel-concrete frame



(b) Beam-column connection details with skew webs

Fig. 1. Steel frames encased in precast concrete with heavy stiffeners and multiple bolts.

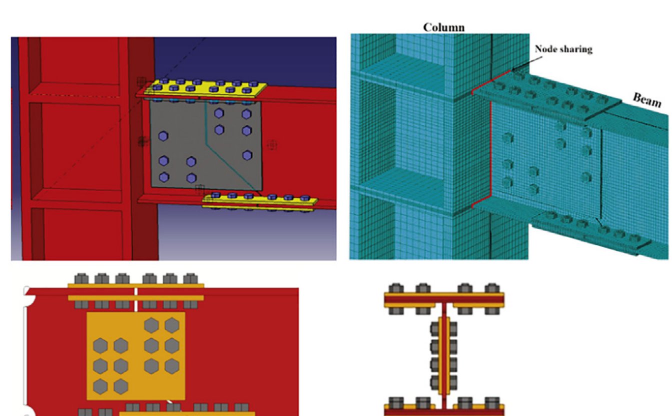


Fig. 2. Finite element meshes of the proposed joint.