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Dimensional analysis of the slotted bolted connections against impulsive earthquake ground motions

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ABSTRACT

The slotted bolted connections (SBCs) are modified bolted connections designed to dissipate input energy through friction slippages during static and dynamic cyclic loadings. Over the recent years, SBCs have received more implementations in buildings with steel moment resisting frames as their ductile behaviors are highly compatible with other connection details against earthquakes, such as the self-centering post-tensioned (PT) steel beam-to-column connections. Hence, it becomes necessary to properly characterize and grasp their dynamic responses. In order to systematically evaluate the effectiveness of SBCs, the dimensional analysis is used in this study to quantify the connection responses as the function of input ground motion characteristics and SBC model parameters. To facilitate this, a simplified yet parameterized numerical model is first proposed to mimic the observed responses of the tested prototype steel SBC. By comparing the dimensionless structural responses of the regular bolted welded connection with that of the SBCs when subject to various pulse type motions, the effectiveness of the presented SBCs is investigated thoroughly. Then, a parametric study is presented based on the nonlinear dimensional spectra, where each of the variables that contribute to the SBC effects was studied in details. Finally, some design recommendations are provided based on the observed results.

1. Introduction

Comprehending the nonlinear behavior of structural systems and elements subjected to external loading is an important component of structural engineering. Steel moment resisting frame (SMRF) design, construction, and performance evaluation, for instance, has benefitted from accelerated advances in the state of knowledge over the past two decades. Historically, suffering severe earthquakes such as the 1994 Northridge and the 1995 Kobe earthquake, the typical welded steel moment frame connections failed to provide the expected ductile behaviors, which lead to the damages such as the fractures of full penetration welds, the cracks in beam flanges, and the cracks through the column sections [1]. Consequently, the SAC joint venture was initiated to investigate the performance problems of steel moment frame connections. The outcome of this project was a series of Federal Emergergency Management Agency (FEMA) guidelines and reports covering areas such as new construction [2] and renovation of existing structures [3] based on numerous connection tests and numerical studies [4,5].

The FEMA reports suggest that a connection could not only form a plastic hinge, but also dissipate energy during seismic events. Consequently, the passive control systems such as the metallic and various hysteretic dampers were invented to dissipate energy without power sources [6–9]. In most passive control systems, such as a metallic plate damper or a Buckling Restrained Brace (BRB), the input energy is dissipated by sacrificial elements which are replaceable after the earthquakes [10–14].

However, observed from the 2010/2011 Christchurch earthquakes, a structure might suffer collapse if the location and extent of the damages are not well controlled. There has thus been interest in low damage seismic-resisting systems in recent years. The slotted bolted connection (SBC) are regarded as a type of friction damper or the slip-friction connectors, which provides inelastic deformation and energy dissipation through frictional sliding, as opposed to yielding of sacrificial members. The SBCs are easily installed, require less replacement costs, and have stable ductile behaviors [15–17]. In addition, they provide a reliable friction damping mechanism that is compatible with other connection details. For example, many researchers have combined the SBCs with the post-tensioned (PT) steel beam-to-column moment connections, which help to reduce the post-earthquake damages by providing re-centering capacities to the connections [18–22].

The ductile performance of the SBC is remarkable, dissipating significant amount of seismic energy [23,24]. FitzGerald et al. [15] concluded two states of the SBC performance, where the first state was the friction state with no strength hardening and the second state included the strength hardening at a larger deformation level. The load carrying capacity as well as the ultimate stiffness for the second state became larger due to the increase of the shear force between the bolts and the flange

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plates. In addition, existing studies found that a typical SBC usually demonstrate force pinching phenomena due to contact phenomena and plastic deformation [25,26]. However, limited studies have compared the full nonlinear behavior (i.e. the pre- and post-yielding stiffness, the ductility, the deterioration of strength and stiffness) between the regular bolted connections (RBCs) and the SBCs.

In this paper, the mechanism and behavior of a prototype steel SBC is first reviewed to develop a simplified numerical model for describing its force-displacement relationship. The ductile behavior of the connection is then evaluated under the framework of dimensional analysis. By comparing the dimensionless displacement and total acceleration, the effectiveness of SBC and recommended SBC model parameters can be comprehensively evaluated. With appropriate selections of SBC model parameters, one could systematically understand the dynamic ductile behaviors for such type of SBCs.

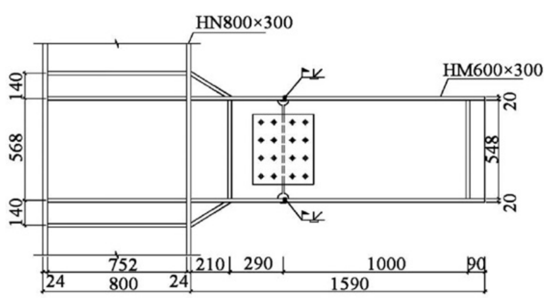
2. The tested and simulated SBC responses

To comprehend the behavior of SBCs, a classical SBC for SMRFs was first designed and tested in the lab. The column and beam were sampled from a 4-Bay 7-Story steel moment frame, which was designed according to the Chinese structural design code [27].

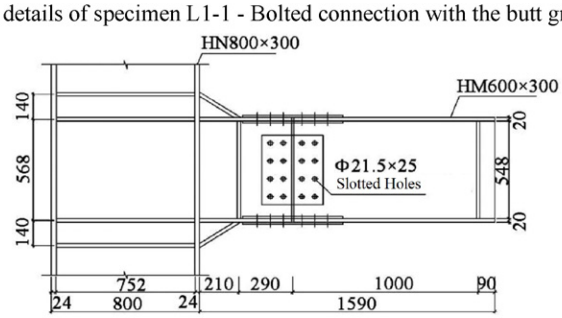
2.1. The experimental results

Four connection specimens were designed, fabricated, and tested in the lab. The column section was HN800 × 300 (800 mm height, 300 mm width, 26 mm flange plate thickness, and 14 mm web plate thickness) and the beam section was HM600 × 300 (600 mm height, 300 mm width, 20 mm flange plate thickness, and 12 mm web plate thickness). The column and beam were made of steel Q235 with yield stress 235 MPa. The strength of the column was higher than the strength of the beam. Therefore, the major deformation of the system was expected at the beam-to-column connection on the beam. The experimental layout as well as the specimen configurations was detailed in another study [25]. Hence, this study will only highlight the key features of the experiment for completeness of the study.

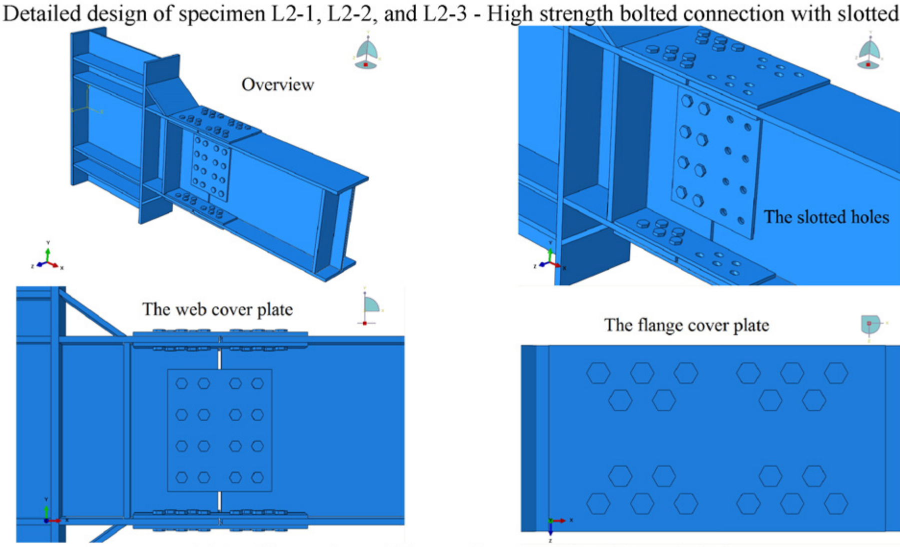
Fig. 1(a) shows the specimen L1-1, which was a RBC specimen. The connection for the specimen was fully butt groove welded and the webs of the two pieces were bolt connected. The other specimens (i.e.



(a) Design details of specimen L1-1 - Bolted connection with the butt groove weld



(b) Detailed design of specimen L2-1, L2-2, and L2-3 - High strength bolted connection with slotted holes



(c) 3D illustrations of the specimens L2-1, L2-2, and L2-3

Fig. 1. The tested specimens and the 3D view of the SBC specimens.