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Welded haunches for seismic retrofitting of bolted T-stub connections and flexural strengthening of simple connections

Hamid Saberi [a,*], Ali Kheyroddin [b], Mohsen Gerami [b]

[a] Department of Civil Engineering, Semnan University, Semnan, Iran
[b] Civil Engineering Faculty, Semnan University, Semnan, Iran

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ABSTRACT

There are wide variety of techniques for seismic rehabilitation of structures. Selecting the optimum technique for rehabilitation of existing structures has been a challenge for engineers in the recent years. One of rehabilitation cases is to retrofit rigid connections in steel moment frames by making the least changes. Another case is rehabilitation of steel braced frames with pinned connections whose high relative displacements during an earthquake increase the collision probability for adjacent structures. In this paper, welded haunches as a technique for rehabilitation of bolted T-stub connections with weak bolts or weak T-stub flange as well as a technique for changing pinned connections to moment connections is experimentally investigated. Six corner connection specimens are made and tested under SAC cyclic loading protocol. The results of this study show that this rehabilitation technique not only modifies the cyclic behavior of weak rigid connections and changes simple bolted connections into moment connections, but also it improves the behavior of the rehabilitated connections in a way that their behavior is more desirable than that of the reference rigid connection designed according to AISC. For example, flexural capacity and rotational stiffness of the retrofitted connections are higher than those of the reference connection by 30 and 70% in average respectively. Furthermore, the connection failure potential in this rehabilitation technique is reduced by transferring the plastic hinge to the after-haunch area far from the connection area. The use of this rehabilitation technique in bolted connections with weak T-stub flange provides better cyclic behavior compared to that of a connection with weak bolts, since higher flexural capacity and energy dissipation is reached. The results show that this technique can be used for rehabilitation of adjacent simply braced frames without adequate separation distance to reduce the collision probability in earthquakes.

1. Introduction

There are wide variety of techniques for seismic rehabilitation of structures. One of rehabilitation cases is to retrofit rigid connections in steel moment frames by making the least changes, since it is difficult to make many changes in the existing connections. Another case is rehabilitation of steel braced frames with pinned connections whose high relative displacements increase the collision probability for adjacent structures. An example of such cases is the adjacent structures with inadequate separation distance where there is high risk of collision during an earthquake. The first goal of this investigation is to evaluate the use of welded haunches as a technique for rehabilitation of bolted T-stub connections with weak bolts or weak T-stub flange, in a way that the retrofitted connections can be used in special moment frames. According to the recommendations of FEMA350 [1], "The connection shall be designed so that inelastic behavior is controlled either by flexural yielding of the beam in combination with shear yielding of the column panel zone, or by flexural yielding of the beam alone.". It is also emphasized by FEMA350 [1] that "Brittle fracture in the connection zone is undesirable.". Moreover, connections can be used in special moment frames whose failure modes are the formation of plastic hinge in beam and the flexural capacity reductions do not exceed 20% until reaching the rotation of 0.04 rad. The second purpose of this study is to investigate the applicability of this rehabilitation technique in changing pinned connections to moment ones and consequently, reduce the drift in simple braced frames. In the followings, some researches in the recent years in the field of connections and the rehabilitation techniques are reviewed.

* Corresponding author.
E-mail addresses: saberi.hamid@gmail.com (H. Saberi), kheyroddin@semnan.ac.ir (A. Kheyroddin), mgerami@semnan.ac.ir (M. Gerami).

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The use of a haunch on the bottom side of the beam to enhance the seismic performance of damaged steel moment frame connections has been proposed by Uang et al. [2] after the 1994 Northridge earthquake. The effectiveness of such a scheme was demonstrated through both static and dynamic testing of four full-scale specimens by the same authors. Static and dynamic test results showed that the cyclic performance could be significantly improved and the plastic hinging of the beam occurred away from the face of the column.

Seismic design of steel moment connections with welded straight haunch was performed by Lee and Uang [3]. The authors stated that welding a straight haunch beneath the beam could be a viable solution for repair and rehabilitation of pre-Northridge moment connections and also new construction. Also a simplified analytical model that considers the force interaction and deformation compatibility between the beam and haunch was developed.

Cyclic seismic testing of steel moment connections reinforced with welded straight haunch was done by Lee et al. [4]. The tests demonstrated that a sloped edge combined with a drilled hole near the haunch tip, or a pair of stiffeners that partially or fully extended from the beam web, successfully prevented crack initiation at the haunch tip.

Maximum strength and optimum haunch length of steel beam-end with horizontal haunch was evaluated by Tanaka [5]. He has proposed a design method based on twenty-nine horizontally haunched beam specimens. This method produces ductile beam-to-column connections. A rough value of the optimum haunch length is about 25–35% of the beam depth.

A series of five full-scale subassemblages were tested by Kim et al. [6] to investigate the contribution of the slabs and the effects of three types of retrofit methods, no weld access hole, horizontal stiffener, and cover plate. The test result indicated that the strains near the bottom flange of the composite beam connections were several times larger than those of the bare steel beam connections, resulting in a higher potential of fracture. Horizontal stiffener detail of three retrofit schemes demonstrated very good potential in improving the ductility of composite connections in existing buildings.

Xu and Ellingwood [7] investigated the performance of steel frames with partially restrained connections fabricated from bolted T-stubs following damage to load-bearing columns. Their analysis indicates that the frames with strong T-stub connections can resist collapse in damage scenarios involving notional removal of one first-story column, while the robustness of the frames with weak T-stub connections is questionable.

The behavior of steel–concrete composite haunch beams was investigated by Ng et al. [8]. Experiments were carried out to investigate the ultimate load behavior of haunch composite beams. Experimental results showed that composite haunch beam exhibits a ductile moment–rotation behavior and is able to redistribute moment to the mid-span by loss of stiffness due to cracking of concrete slab and yielding of either steel reinforcement or cross section.

Saberi et al. [9] have explored comparison of bolted end plate and T-stub connection sensitivity to bolt diameter on cyclic behavior. The results showed that the bolted T-stub connections are more sensitive to bolt diameter rather than end plate connections. Hence, the bolted end plate connections are recommended where the imperfection in construction or changes in function of the building is probable.

Asada et al. [10] proposed a method to improve plastic deformation capacity of the welded wide flange beam-to-column connections in existing steel buildings by using supplemental H-section haunches jointed by high-strength bolts and welding which expected to secure construction quality. As a result, it could prevent the fracture of beam flange initiated from toe of weld access hole. Cumulative plastic deformation capacities of retrofitted specimens were 1.5–2.0 times larger than that of un-retrofitted specimen.

Stiffness modeling of bolted thick built-up T-stub connections including secondary prying effect was done by Hantouche et al. [11] closed form expressions that are based on stiffness modeling techniques are developed to predict the energy dissipation capacity of the T-stub/column flange system with and without continuity plates.

A simple approach for seismic retrofit of low-rise concentric X-braced steel frames was proposed by Grande and Rasulo [12]. They developed a retrofit procedure for concentric steel braced frames (CBFs) and applied to some cases of study.

A simple simplified FEM model of a bolted T-stub with only one bolt row has been developed by Francavilla et al. [13]. They used SAP2000 computer program aiming to show how even a wide-spread commercial software can be used to estimate the plastic deformation capacity of bolted joints' components.

T-stub behavior under out-of-plane bending was investigated by Gil and Goñi [14]. The connection characteristics have been obtained by means of tests and finite element models, and after comparison with the limits provided by the Eurocode 3, it is concluded that all connections under study are indeed semi-rigid and partial strength.

Seismic response of modern steel moment resisting frames (MRFs) with partially-restrained bolted beam-to-column connections was evaluated by Brunesi et al. [15]. A numerical procedure, based on detailed three-dimensional solid and one-dimensional fiber-based finite element (FE) models, has been developed and validated using past experimental results.

The non-linear behavior of a T-stub joint exposed to impact loads have explored by Ribeiro et al. [16] numerically. The results show that different dynamic loads have minor effect on the force displacement response, whilst the load application time has a larger effect.

2. Test specimens

In this paper, 5 rigid bolted T-stub beam-to-column connections and a simple bolted top and seat angle connection are tested. The connections represent a corner connection according to the sub-structure suggested by FEMA350 [1]. Beam profile in all specimens is IPB140 with 1.5 m length and the column profile is IPB200 with 2 m length. As previously noted, the first goal of this investigation is to evaluate the use of welded haunches as a technique for rehabilitation of bolted T-stub connections with weak bolts or weak T-stub flange, in a way that the retrofitted connections can be used in special moment frames. To investigate the mentioned purposes, a reference specimen called TS-R (T-Stub Reference) is designed and constructed according to AISC requirements [17]. Two weak specimens, one with weak bolts called TS-WB (T-Stub Weak Bolt) and the other with weak T-stub flange called TS-WP (T-Stub Weak Plate) are fabricated. To evaluate cyclic behavior of the retrofitted connections using the proposed method, these two weak specimens are fabricated again and retrofitted by welded haunches and called TS-WB-H15 and TS-WP-H15. Moreover, the second purpose of this study is to investigate the applicability of this rehabilitation technique in changing pinned connections to moment ones and consequently, reduce the drift in simple braced frames. To investigate the mentioned goals, specimen T&S Angle-H15 which is a simple bolted top and seat angle connection is retrofitted by welded haunches and tested. Details of the specimens are presented in Fig. 1 and Table 1. The actual material properties of the steel and bolts are obtained from tensile tests on coupons and from the bolt certificate of quality as shown in Table 2. The nominal