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Cyclic response sensitivity of post-tensioned steel connections using sequential fractional factorial design

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ABSTRACT

Through the use of post-tensioned (PT) elements in steel beam-column connections, steel buildings under seismic excitations can return to their plumb position, displaying negligible permanent deformation. The cyclic behavior of a PT connection is affected by several design parameters. This paper aims at identifying the significant factors which affect the cyclic response of steel PT connections with top-and-seat angles. A sequential fractional factorial design-of-experiment methodology is used to statistically evaluate the effects of different design factors as well as their interactions on the cyclic response of PT connections. To this end, 3D finite element models are first developed to accurately simulate the cyclic behavior of the connections. After validating the finite element results with the past experimental data, a two-stage (sequential) sensitivity analysis is conducted. Eight potential factors, including the material and geometric properties of steel angles, reinforcing plates, and bolts, are considered. The cyclic response of connections is examined in terms of stiffness, strength, energy dissipation capacity, and residual displacement. From this parametric study, the significance of the design factors is determined with respect to each response. Additionally, regression models are presented to estimate the response quantities for other PT connection configurations with the same beam and column sections.

1. Introduction

In current seismic design codes, steel buildings are designed to ensure that the collapse of buildings and loss of lives are prevented. Buildings are expected to resist seismic loads while being ductile enough to undergo large deformations [1]. Consequently, steel buildings may suffer extensive damage in the form of material yielding, fracture and buckling of structural steel elements. Following an earthquake, the incidence of permanent damage in a building increases repair costs. Large permanent deformations can even make the repair of buildings prohibitive, and ultimately, demolition of severely-damaged buildings could be required. In the 2010 and 2011 Canterbury earthquakes, over 150,000 homes were damaged. A rebuild cost of around $20 billion (New Zealand dollars) was estimated, not including disruption costs and insured losses [2]. In the central business district and suburbs, 1600 buildings needed to be demolished [3]. For a large city with damaged, non-serviceable buildings, the economic losses are significant. The repair of buildings with residual deformation of over 0.5% may not be economically feasible [4].

Previous research highlights the importance of accounting for residual deformations when designing buildings for seismic loads [5–7]. Along with these efforts, research continues in mitigating residual deformations of buildings subject to earthquakes [8,9]. Over the past 20 years, there has been a growing interest in seismic resilient buildings with self-centering capabilities [10–13]. In such buildings, certain elements are used so as to provide restoring forces, and thus eliminate (or control) residual deformations after earthquakes. Several self-centering systems have been previously investigated for steel buildings, using different mechanisms for energy dissipation and self-centering capability. Examples of these self-centering systems are steel buildings with shape memory alloy (SMA) bracing [14–16] and SMA-based connections [17–19], self-centering energy dissipative braces [20–22], rocking systems [23–25], and steel plate shear walls [26,27]. Another approach to self-centering is to use post-tensioned (PT) elements in steel moment resisting frames [28].

Over the past two decades, several kinds of energy dissipation mechanisms have been examined for PT steel beam-column connections. Fig. 1(a) illustrates a PT beam-column connection with top-and-seat angles. In a PT steel moment frame, beams are compressed to columns using horizontal PT elements (strands or bars). Ricles et al. [29] performed nine experimental tests to investigate the cyclic performance of PT connections with top-and-seat angles. It was confirmed that self-centering is achieved using PT strands, while

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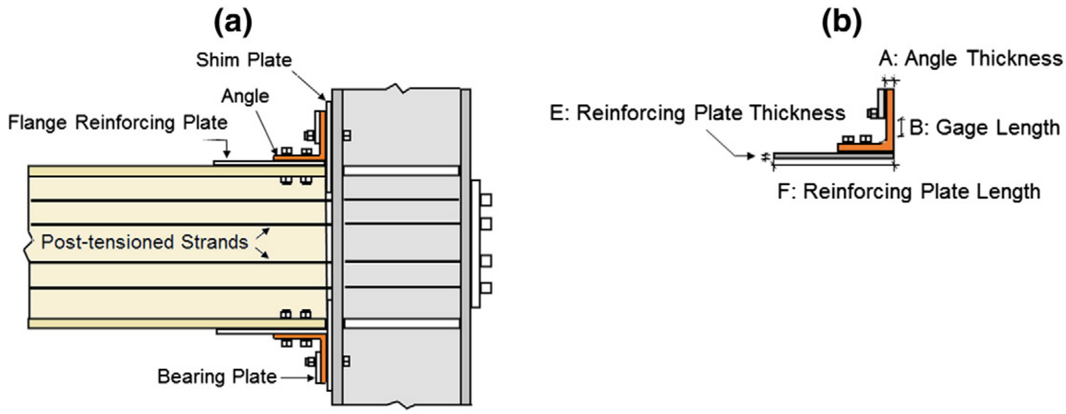

Fig. 1. (a) Schematic of an exterior self-centering beam-column connection with PT steel strands, (b) Geometric factors considered in the sensitivity study (factors *A*, *B*, *E*, and *F*).

damage is essentially confined to replaceable top-and-seat angles. The test results demonstrated that PT connections display excellent stiffness, strength, and ductility. Further tests [30] with larger beam sections introduced PT connections as a vital alternative to conventional welded connections. Researchers have also studied PT beam-column connections with other energy dissipation mechanisms. Examples of those systems are PT connections with buckling-restrained energy dissipative steel bars (e.g., [31]), PT connections with friction devices [32,33], and PT connections with web hourglass shape steel pins [34].

2. Motivation and objective of this study

In this paper, the sensitivity of cyclic response of PT connections to different design variables is examined. The variability of the cyclic response to a number of individual factors such as thickness of steel angles has been addressed in previous research [29]. However, to investigate response sensitivity of multiple factors at the same time, a factorial analysis is required. By varying different factors together, the effect of each factor is assessed. Further, any possible interaction between factors is determined. An interaction is statistically active when the effect of one factor on the response changes at different levels of another factor. For the present study, first, an efficient finite element model is generated and validated against experimental data in [29]. Then, two-level factorial designs with eight factors are generated to evaluate the influence of each factor on the cyclic response. The selected factors include geometric and material properties of steel angles (thickness, gage length, and yield strength), thickness and length of reinforcing plates, bolt pretension force and bolt yield strength, and post-tension force in high strength steel strands. The cyclic force–displacement response of PT connections is examined in terms of different characteristics, including stiffness, load capacity, hysteretic energy dissipation, and residual displacement. In addition to evaluating the significance of different factors associated with each response characteristic, predictive equations are presented. The accuracy of the predictive equations is verified by comparing the response quantity from regression models with that from finite element analysis. Overall, using a two-stage fractional factorial strategy, 56 finite element models of PT beam-column connections with top-and-seat angles are analyzed, including the final verification models. The results to be presented in the following sections would be useful in practice for performance optimizations of PT steel beam–column connections.

3. Finite element model

To simulate the cyclic behavior of PT steel beam–column connections, 3D finite element models were developed and analyzed in FE software ANSYS [35]. In order to calibrate the finite element models and verify simulation results, two of the PT connection specimens

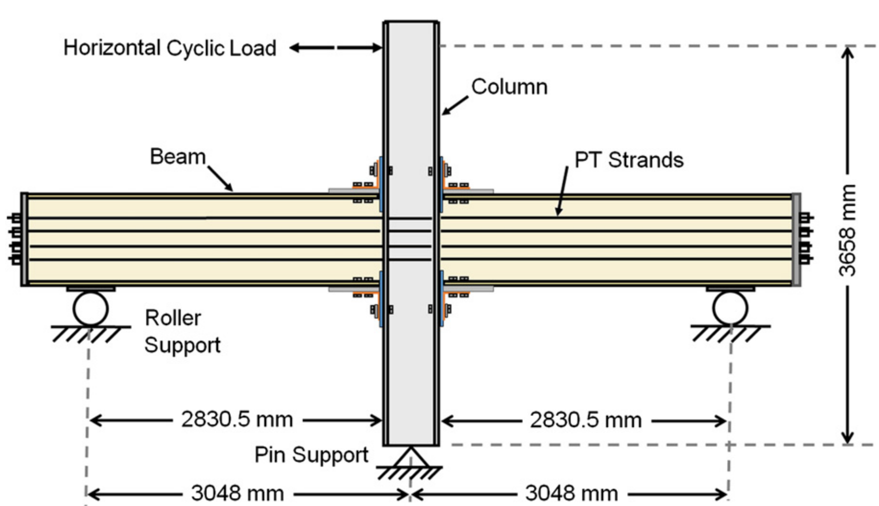

Fig. 2. Interior PT connections considered (adapted from [29]).