Engineering Structures 130 (2017) 180–197

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Multi-criteria optimization of lateral load-drift response of posttensioned steel beam-column connections

Saber Moradi PhD [1,2], M. Shahria Alam PhD *

School of Engineering, The University of British Columbia, 1137 Alumni Avenue, Kelowna, BC V1V1V7, Canada

ARTICLE INFO

Article history:
Received 12 July 2016
Revised 6 September 2016
Accepted 4 October 2016
Available online 18 October 2016

Keywords:
Posttensioned steel connection
Beam-column connection with bolted angles
Finite element modeling
Self-centering
Multi-criteria optimization
Response surface method

ABSTRACT

Posttensioned (PT) elements in steel buildings can substantially mitigate permanent seismic damages and the associated post-earthquake repair costs during earthquakes. In this paper, a response surface methodology (RSM) is used to predict and optimize the lateral response characteristics of PT steel beam-column connections with top-and-seat angles. The monotonic lateral response characteristics considered in the study include: initial stiffness, load capacity, and ultimate drift of PT connections, as well as load and drift levels corresponding to the gap-opening (decompression) in PT connections. Based on the results of finite element simulations and extensive sensitivity studies, six influential parameters are considered as input variables in this study. These parameters are posttensioning strand force, beam depth, beam flange thickness and width, span length, and column height. By using a desirability approach, the lateral response of PT steel beam-column connections is optimized. The optimization studies aim at maximizing the initial stiffness, load capacity, and ultimate drift of PT connections and/or minimizing the amount of steel in the beam section, which contributes to the final cost of frame structures. The multi-criteria optimization studies reveal the regions of factor space where optimal conditions are achieved. The optimized solutions are then confirmed by performing simulation runs with the optimal factor combinations. Among the results, it is shown that damage occurs earlier in PT connections with deeper beams and greater posttensioning strand forces. The dominant limit state for the PT connections was beam local buckling starting at early drifts of 1.2%, whereas the first occurrence of angle fracture was at about 4% drifts, and two limit states of strand yielding and bolt extensive yielding were not observed in the analyzed PT connections.

1. Introduction

Welded beam-column connections in steel moment resisting frames suffered brittle fractures during the 1994 Northridge earthquake [1]. Following this unexpected damage, researchers aimed to improve the seismic performance of steel moment frames. In an effort to avoid possible defects and uncertainties associated with the welding at the beam-column interface, several connection details have been proposed. These modifications that are primarily intended to shift the location of plastic hinges away from the column face include the use of reinforcing plates and reduced beam sections [2]. Despite improved seismic performance, these connections sustain permanent damage to main structural members under strong earthquakes – due to yielding and local buckling of beam sections, steel buildings suffer permanent deformations under earthquake excitations. Large residual deformations, in turn, increase repair costs and result in large economic losses associated with demolition and collapse [3].

To prevent residual deformations in steel buildings, researchers have investigated several self-centering systems by which the structure can return to its original position following an earthquake. One self-centering technique is to use posttensioned (PT) strands/bars in buildings. Posttensioning offers an efficient and cost-effective strategy for eliminating permanent deformations. The self-centering capabilities – restoring forces – are provided by high-strength steel elements while supplemental energy dissipating devices or fuses are often incorporated in the structure to dissipate energy. The response of such self-centering buildings is characterized by a gap opening mechanism occurring at the

* Corresponding author at: School of Engineering, The University of British Columbia, 1137 Alumni Avenue, EME 4225, Kelowna, BC V1V1V7, Canada.

E-mail addresses: saber.moradi@ucla.edu, sbrmor@gmail.com (S. Moradi), shahria.alam@ubc.ca (M.S. Alam).

[1] Address: Postdoctoral Scholar, Civil & Environmental Engineering Department, The University of California, Los Angeles, 2541 Boelter Hall, Los Angeles, CA 90095-1593, United States.

[2] Former affiliation: Ph.D. Candidate, School of Engineering, The University of British Columbia, 1137 Alumni Avenue, EME 3213, Kelowna, BC V1V1V7, Canada.

http://dx.doi.org/10.1016/j.engstruct.2016.10.005
0141-0296/

building foundation, beam-column connections, or/and within structural members, such as braces [4]. Rocking steel frames, which allow columns to uplift at the foundation level [5–7]; PT beam-column connections [8]; self-centering energy dissipative braces [9,10]; and self-centering frames with PT base column connections [11] are few examples of research on self-centering steel buildings with PT elements.

Past studies have demonstrated the viability of PT steel beam-column connections as efficient and relatively inexpensive systems for providing restoring forces in steel buildings. PT steel connections with beams posttensioned to columns can be classified into two primary groups of self-centering systems depending on the energy dissipating mechanism used. These two categories include: (1) PT connections with yielding based devices or elements, such as top-and-seat angles [12–14], buckling-restrained steel bars [15], buckling-restrained reduced flange plates [16], beam bottom flange steel plates [17], hourglass pins attached to the beam web [18], and (2) PT connections with friction based devices [19–21].

2. Scope and methodology

Previous research on the analysis, design, and assessment of PT steel beam-column connections has shown promising results (for example, [8,12,13]). However, a thorough study is needed to statistically investigate the relationship between the lateral load response of PT connections and influential factors. It is critical to find and assess optimized factor regions where the efficiency of PT connections can be improved.

In this study, the lateral response characteristics of PT connections are assessed and optimized using validated finite element simulations [22,23]. Fig. 1 shows a schematic view of the PT beam-column connection subassemblies considered in this study. Six influential parameters identified in previous sensitivity studies [23,24] are considered, including: posttensioning force, beam depth, beam flange thickness and width, span length, and height (column length). Response variables considered are: initial stiffness, decompression force, load capacity, decompression drift level, and maximum drift level. Different phases of the study are summarized in Fig. 2. A response surface methodology (RSM) is used to predict the response characteristics. Response optimization studies are then performed using a desirability approach. The accuracy of the predictions and optimization results is next confirmed by performing confirmation studies.

3. Factors and response variables

From the results of previous sensitivity analyses [23,24], six most influential parameters were chosen for this response surface study. These factors and their ranges are listed in Table 1.

Five response variables were considered. As illustrated in Fig. 3, these response variables are: initial stiffness (K_i), decompression force (F_{deco}), maximum load capacity (F_{max}), decompression drift (θ_{deco}), and maximum drift (θ_{max}). In this figure, H is the column height.

Design of experiment (DOE) was used as an efficient method to construct sampling data points (factor combinations). The observation, measurement, or computation of a response (y) with a certain factor combination is termed as an experiment. Factorial designs and central composite designs are examples of experimental designs. Since there is no random error in a computer experiment, some of the methods for the designs with physical experiments may not be ideal for computer-based experiments [25]. Therefore, we used an I-optimal design that is more appropriate for computer experiments with the goal of predicting and optimizing the response rather than estimating coefficients of a model [26]. The algorithm for this I-optimal design is to choose runs that minimize the integral of the prediction variance across the factor space. That is, the design points (factor combinations) are chosen in a way that the average variance of prediction is minimized over the design space. The I-optimal design listed in Table A1 is generated by using Design-Expert software [27]. The factors C, D, E, F, H, J in Table A1 are those input parameters defined in Table 1. Design-Expert software is a statistical analysis software for design of experiment. This commercially available software provides several statistical tools useful for studies aimed at finding influential factors, developing predictive models, and optimizations.

A total of thirty-three models of PT connections (with the input parameter combinations in Table A1) were developed and analyzed in ANSYS. The limit states monitored in this study include: beam local buckling (BLB), angle fracture (AF), strand yielding (SY), and the extensive yielding of tensile bolts (boltY). The criteria for identification of each damage state can be summarized as follows: strand yielding is assumed to occur when the maximum tensile force in a PT strand reaches 80% of the strand ultimate strength. The bolt extensive damage state corresponds to a critical tensile strain of 2.5% in a tensile bolt. Lastly, the angle fracture limit state is assumed to occur when any of these three thresholds is reached: gap-opening between the beam and column (=32 mm), Plasticity Index (=174), and Rupture Index (=70%) These damage identification measures were established based on experimental and simulation results. Further details can be found in [23,30].

4. Discussion of lateral response and limit state behavior

In properly designed frames with PT steel beam-column connections, seismic damage is expected to be confined to energy dissipating elements (steel angels in PT connections with bolted angles); therefore, the main structural members, such as beams and columns, remain essentially elastic. PT steel connections are typically capable of providing self-centering behavior under lateral loads unless certain damage states occur. These limit states which may be substantial to prevent a PT frame from returning to its plumb position include: beam local buckling, angle fracture, and PT strand yielding. Further explanations of the lateral response and limit state behavior of PT steel connections with top-and-seat angels can be found in previous research (for example, in [12,23]).

For the models of PT connections analyzed in this study, wide ranges of response variables were observed (see the plots illustrated in Figs. A1 and A2). A list of the response variables computed from each simulation run is provided in Table 2, as well as the governing damage or limit state, which occurred first in the PT connections. Examples for the monotonic lateral load-drift response are shown in Fig. 4 for PT connection models 1, 14, 23, and 33. The governing limit state for connection 23 is angle fracture while beam local buckling occurs in the other three connections. Fig. 5 shows the beam local buckling in connection model 1 at 1.4% drift.

The limit state of beam local buckling occurs at a drift as early as 1.2% in model 15. This early beam buckling is attributed to the high posttensioning strand force and low beam flange thickness and width. As also other instances indicate, deeper beams are generally more prone to early beam local buckling (models 15, 21, 24, and 32). When comparing the drifts at which early beam local buckling or angle fracture occurs, it can be stated that beam local buckling is more dominant in the connection models analyzed. The earliest occurrence of beam local buckling is at 1.2% drift (model 15) whereas the earliest angle fracture is at a drift of about 4% (model 8).

The connection model 8 has a low posttensioning strand force, deep beams, high beam flange thickness, and a low span length. A