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Seismic design of bridge columns incorporating mechanical bar splices in plastic hinge regions

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ABSTRACT

The application of prefabricated bridge elements dates back to more than half a century. Several prefabrication techniques have been developed thereafter for capacity protected bridge elements. However, the application of precast bridge columns in moderate and high seismic regions is scarce mainly because of a lack of performance data pertaining to their connections. One of the precast column connections that has been recently emphasized for accelerated bridge construction (ABC) utilizes mechanical bar splices, which are commonly referred to as couplers. For ABC, couplers have to be generally used in the plastic hinge region of precast columns. This would violate the current bridge seismic design codes ban on the application of couplers in the plastic hinge regions of ductile members. The present study was conducted to (a) identify suitable mechanical bar splices for precast column connections through a state-of-the-art review, (b) develop a generic material model for all coupler types, (c) quantify the coupler effects on the column seismic performance, and (d) develop simple design equations for plastic hinges to facilitate the design and field application of mechanically spliced columns in moderate and high seismic regions. It is proposed that the current code limitation on couplers in plastic hinges be revised based on the findings of the present study.

1. Introduction

The application of prefabricated bridge elements in the USA dates back to more than half a century ago when the Walnut Lane Memorial bridge was built in 1951 utilizing precast prestressed girders [1]. Thereafter prefabrication has been utilized in other bridge elements but mainly limited to those that are referred to as "capacity protected elements" with no significant nonlinear deformations expected under seismic loads. Accelerated bridge construction (ABC), which utilizes new techniques, advanced planning, and novel detailing to expedite construction, relies heavily on prefabricated reinforced concrete members. Pilot studies indicated that the application of precast columns in seismic zones is limited due to uncertainties in the seismic performance of column connections [2–4].

One method to connect precast columns to adjoining members is through the use of mechanical bar splices commonly referred to as couplers. Even though current seismic codes prohibit the application of couplers in the plastic hinge region of columns in high seismic zones (e.g. AASHTO Seismic Guide Specifications [5], Article 8.8.3), recent studies (presented in the subsequent section) have revealed the feasibility of precast columns utilizing couplers in the plastic hinges, thus provide the opportunity to expand ABC in moderate and high seismic zones.

Several types of couplers are available in the market and new types are emerging. The primary role of the couplers is to shorten the splice length and to reduce bar congestion in the connection. Since bridge columns are the focus of the present study, couplers that transfer both tensile and compressive forces are investigated. Five of the readily available couplers are: (1) shear screw couplers, (2) headed bar couplers, (3) grouted sleeve couplers, (4) threaded couplers, and (5) swaged couplers. Fig. 1 shows the five coupler types. Shear screw splices (Fig. 1a) consist of a coupling sleeve with lock-shear screws and shear rails. Equal lengths of reinforcing bars are inserted into the sleeve, then the screws are tightened until the screw heads shear off. Tension is transferred between the bars through the bearing of the bars against the shear rails inside the couplers and shear in the screws. In headed bar couplers (Fig. 1b), a head is formed on the anchoring end of each bar, then the threaded coupling pieces are torqued to complete the connection. The bars are inserted into a steel sleeve then the sleeve is filled with a non-shrink high-strength grout in the grouted sleeve

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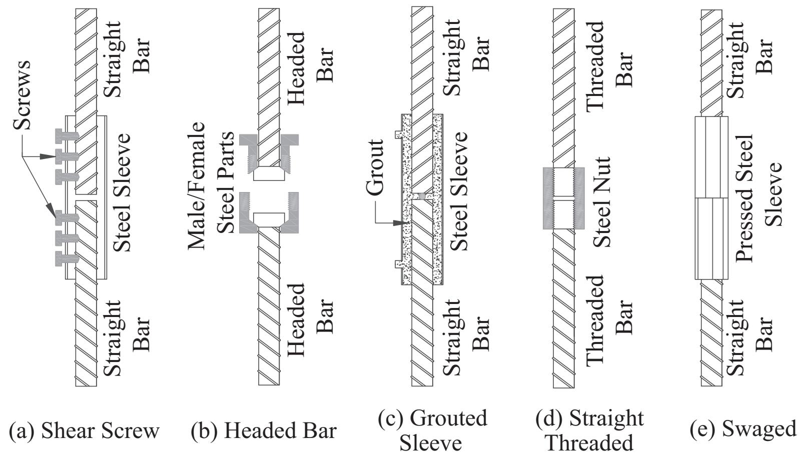

Fig. 1. Typical tension-compression mechanical bar splices.

coupler types (Fig. 1c). Tension is transferred through bond between the bar, grout, and the sleeve. A version of grouted couplers is threaded at one end to shorten the coupler length (threaded-grouted sleeve couplers). In threaded couplers (Fig. 1d), the bars are threaded at the ends and connected to a coupling sleeve with matching internal threads to complete the connection. The threaded portion of the bar can be either straight (or parallel) or tapered. Swaged couplers (Fig. 1e) are formed by pressing a steel sleeve using a hydraulic machine to grip the bar. Tension is transferred between the bars through the swaged sleeve. Note that there might be several manufacturers producing the same type of couplers, thus the proposed categorization is general. For example, there are eight different shear screw couplers at the time of this writing produced by different manufacturers with different screw sizes, screw numbers, and sleeve lengths [6].

In the study presented herein, a state-of-the-art literature review was conducted focusing on the coupler performance under tensile loading and on the seismic performance of columns incorporating couplers in the plastic hinge regions. Then, a set of criteria to accept a coupler for incorporation in the column plastic hinges is presented. A generic stress-strain model was proposed subsequently to facilitate the design of columns with couplers. Furthermore, a comprehensive parametric study was performed to investigate the effect of mechanical bar splices on the column displacement ductility capacity. Finally, a simple design equation as well as a modified plastic hinge length equation were developed to further aid designers in the design of mechanically spliced bridge columns. The ultimate goal of the present study was to facilitate field deployment of mechanically spliced precast bridge columns in high seismic regions.

2. State-of-the-art literature review

2.1. Performance of mechanical bar splices

A summary of pull test results performed on each type of mechanical bar splices is presented in Tables 1–5. Included in the table are the type and size of bars, the number of test specimens, the coupler length, the mode of failure in tensile tests, and highlights of each test. In-depth discussion of different coupler types, their constructability, and tensile testing results of different studies were discussed in Tazarv and Saiidi [32].

Some of the spliced bars with shear screw couplers (Table 1) exhibited lower strength and strain capacity compared to non-

Table 1
Summary of studies on shear screw couplers.

Study	Coupler	Bar size	Bar type	Mode of failure	Remarks
Lloyd [7]	Three-screw, “Bar-Lock L-Series”, Tests: 160, Length: 12.3d_b	No. 6 (Ø19 mm) and No. 8 (Ø25 mm)	ASTM A615 Grade 60	Bar pullout, bar fracture	90% of the ultimate strength of the bar can be achieved, strain capacity was less than 4%
Hillis and Saiidi [8]	Three-screw “Zap Screwlok Type 2”, Tests: 4, Length: 14d_b	No. 4 (Ø13 mm) SMA bars to Steel Bars	NiTi SMA & Grade 60 Steel bars	SMA bar fractured inside the grip	No coupler failure and no SMA bar fracture inside the coupler was observed, strain capacity was 6.9%
Rowell et al. [9]	Seven-screw “Zap Screwlok Type 2”, Tests: 9, Length: 15d_b	No. 10 (Ø32 mm)	ASTM A615 Grade 60	Mainly bar fracture inside couplers	Lower strength and significantly lower strain capacities were observed due to premature failure of bars, strain capacity was less than 2.7%
Huaco and Jirsa [10]	Three-screw (S-series) and four-screw (B Series) Tests: 10, Length < 10d_b	No. 8 (Ø25 mm)	ASTM A706 Grade 60	Bar fractured inside or away from coupler	Bar fractured at the end of the three-screw couplers and bar fractured outside the four-screw couplers, three times higher strain capacity for longer couplers was observed
Alam et al. [11]	Three-screw “Bar-Lock S”, Tests: 9, Length: 8.4d_b	No. 4–6 (Ø13–19 mm)	Grades 40 and 60	Bar fracture	Low slippage was observed before yielding, sufficient strength was reported

Note: “Tests” indicates the number of test specimens, “Length” is the coupler length, d_b is the diameter of the spliced bar, SMA is an acronym for shape memory alloy.