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Bolted steel slip-critical connections with fillers: II. Behavior

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ABSTRACT

Research has been conducted to better understand the effect of fillers in bolted steel connections. In a companion paper, the results of sixteen experiments on bolted steel slip-critical connections with fillers are presented along with proposed design recommendations. In this paper, detailed behavior of the specimens is documented through an examination of deformation and strain response. Additionally, mechanisms are proposed that clarify key aspects of the behavior of bolted connections with fillers, including prediction of slip and shear strengths. A stochastic analysis, using order statistics, is employed to quantify the detrimental effects of multiple possible slip surfaces on expected slip strength. The use of multiple plies and the effects of developing the filler plate are investigated with respect both to the experimental results and the proposed behavioral mechanisms. The results indicate that the use of multiple plies exacerbates the detrimental effects on slip strength and, to a lesser extent, on shear strength. Furthermore, filler development reduces and in many cases eliminates the reduction in slip and shear strengths.

1. Introduction

Often in bolted steel construction, it is necessary to connect members of different depths. In these cases, filler plates are used to provide a common faying surface. The use of filler plates has an influence on the behavior of the bolted connection including the slip strength and ultimate shear strength. Although prior experimental research on bolted connections with fillers is limited, important trends in behavior have been identified. In a series of tests by Lee and Fisher [1], the slip strength of specimens with fillers was found to be approximately 20% less than that of control specimens without fillers. A series of tests by Frank and Yura [2] observed a slip strength reduction of approximately 17% for a connection with a single ply filler and an approximately 46% reduction for a connection with a multiple ply filler. Also observed in this series of experiments was a reduction in the shear strength depending on filler thickness. This finding served as the basis for the bolt shear strength reduction formula in the AISC *Specification* [3]. A recent study by Dusicka and Lewis [4] observed similar trends for fillers up to 25 mm (1 in.) thick, but found that the strength of connections with 51 mm (2 in.) thick fillers was greater than that of thinner fillers, indicating that detrimental effects of adding fillers reach a peak and decrease for larger filler thicknesses.

Borello et al. [5,6] provide a full description of an experimental program that was undertaken to further investigate the effects of various configurations of filler plates on the behavior of bolted steel slip-critical connections. Sixteen full scale specimens were tested to failure. Each specimen consisted of two wide-flange members, connected by two 51 mm (2 in.) thick splice plates, with filler plates provided where required to provide a constant connection depth (e.g., Fig. 1). The bottom column for all specimens was a W14 × 730. The top column was a W14 × 159, W14 × 455, or W14 × 730. The W14 × 159 and W14 × 455 top column specimens required a filler plate of 95 mm (3 3/4 in.) and 41 mm (1 5/8 in.) respectively. Instrumentation included linear variable differential transformers (LVDTs) and strain gages affixed at various locations on the specimens and the load cell of the 13.3 MN (3000 kip) testing machine. The specimens were identified based on the top column nominal weight (in lbs per foot), development (n—none, h—half, f—full), and unique details. Where duplicate specimens were tested, an additional specimen number was added to the end of the designation. For example, the second undeveloped specimen with a W14 × 159 top column was identified as 159n2.

This paper describes the behavior observed in the experimental program and proposes mechanisms to explain the slip and shear strengths documented in the companion paper [6]. Load-deformation response is the primary means of evaluating behavior, with the overall response progressing from a stiff linear response to the stage of slip followed by bolt shear failure. Specimen 455h, with a W14 × 455 top column and half developed filler plate, is representative of typical behavior of all of the specimens and is presented in greater detail in this paper.

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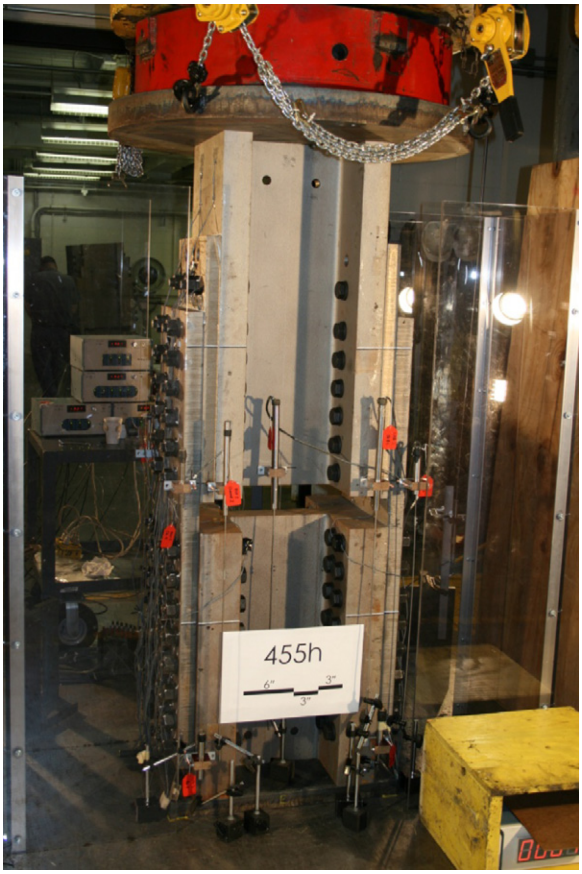

Fig. 1. Typical specimen.

2. Effect of fillers on slip behavior

The displacement and strain measurements (Figs. 2 and 3) show that the behavior of the bolted connections prior to slip is typically linear. Prior to slip, there is no relative motion between the splice plate and filler plate or the filler plate and the top column (Fig. 2). During this stage, the strain measurements indicate relatively uniform introduction of force into the splice plate, as well as slight bending in the splice plates in the gap between the top and bottom columns (Fig. 3). The bending is due to the natural eccentricities existing in the test specimen and has little effect on the behavior of the connection.

Upon reaching the slip load, there was a sudden increase in displacement, corresponding to the slip of at least one of the faying surfaces. The slip event often lasted tens of seconds as the load in the testing machine was stabilized. During this period, stress within the connection was redistributed, as indicated by the offsets in the strain measurements (Fig. 3). Table 1 shows the order in which the various surfaces of each specimen slipped. The order of slip was determined by examining the measured displacements. Frequently, the slip of multiple surfaces occurred within the data sampling period (0.1 s). These surfaces were denoted to have slipped at the same time (e.g., specimen 730-std). In other cases (e.g., specimen 159h), two surfaces slipped at the same load, but the displacement data indicate which of the two surfaces slipped first.

While the average test-to-predicted ratio exceeded unity in this series of sixteen experiments, three specimens slipped prior to the predicted load. One, a specimen with multiple ply fillers (159n-2ply1), failed at 52% of the predicted load [5,6]. Additionally, prior research [1–3] indicates that the use of fillers has a detrimental effect on the slip resistance of bolted connections. An analysis

Table 1
Slip load and sequence of slip per faying surface.

Specimen	Top column/filler plate slip load and sequence		Filler plate/splice plate slip load and sequence	
	North (kN)	South (kN)	North (kN)	South (kN)
730-std	7549[a] (1)	7549[a] (1)	–	–
730-over	7268[a] (1)	7268[a] (1)	–	–
159f	10782 (3)	10782 (3)	5445 (1)	5445 (1)
159h	7549 (1)	7549 (3)	7549 (4)	7549 (1)
159n1	8358 (1)	8358 (1)	8358 (3)	8358 (3)
159n2	7580 (1)	7580 (1)	7580 (4)	7580 (1)
455f	6090 (4)	6090 (3)	6090 (1)	6090 (1)
455h	5227 (3)	5498 (4)	5227 (1)	5227 (1)
455n1	6174 (4)	6174 (3)	6174 (1)	6174 (1)
455n2	6374 (1)	6374 (3)	6374 (4)	6374 (1)
159n-2ply1	4559 (3)	4559 (2)	5333 (4)	2927 (1)
159n-2ply2	5996 (1)	5996 (1)	6143 (3)	6143 (3)
159h-TC	9088 (3)	9088 (3)	7233 (1)	7233 (1)
159n-TC	6921 (3)	5738 (1)	5738 (1)	6921 (3)
159f-weld	–[b]	–[b]	7495 (1)	7495 (1)
159h-weld	11165 (3)	11165 (3)	7188 (1)	7188 (1)

(*x*) Denotes *x*th surface to slip.
[a] Slip between top column and splice plate.
[b] Slip was not achieved.

considering stochastic effects was employed to investigate these observations.

Significant uncertainty is observed in measured values of the slip coefficient [7,8]. When the slip coefficient is considered a randomly varying quantity in connections with more than one faying surface, failure may occur at a load less than would be indicated by a deterministic analysis assuming a single faying surface. Thus, the more slip surfaces there are, the more likely a lower value of the slip coefficient will be present for one of the slip surfaces. Therefore, it is more likely that initial slip of the connection will be at a lower load than in similar connections with fewer slip surfaces. As one example of how to address the detrimental effect of additional slip surfaces, the AASHTO *Specification* limits the number of plies in fillers 6 mm (0.25 in.) thick or greater to at most two, unless approved by the engineer [9].

Statistical data of the slip coefficient are obtained from experimental tests. These tests are, in general, conducted with two slip surfaces, such as the ancillary tests presented in [5,6] (Fig. 4). Many of the slip tests summarized by Grondin et al. [8] follow a similar testing scheme. A distinction needs to be made whether the slip coefficient from these tests is representative of the lower of the two slip surfaces (Assumption A) or the average of the two slip surfaces (Assumption B). A related distinction needs to be made whether failure of the main connection is defined as when the lowest slip strength of any surface in the connection is exceeded (Assumption C) or as when the lowest slip strengths from both sides of the connections are exceeded (Assumption D). These two alternatives relate to the ability of the connection to withstand the eccentricities incurred when one slip surface fails before the other. If the connection is capable of supporting these eccentricities (e.g., has thick splice plates in the configuration of the main specimens), then the slip strength is not realized until the slip resistance of both sides is reached. If the connection is not capable of supporting those eccentricities (i.e., has thin splice plates), then movement occurs on one surface when the lowest slip resistance of either side is reached.

It is reasonable for these tests to assume that the measured slip coefficient from the test is actually the *average* of the slip coefficients of the two surfaces, rather than the *lowest* value of slip coefficient from the two surfaces (Assumption B). This was consistently observed in the ancillary tests presented in [5,6], for example, where the displacement measurements and observations clearly showed that one surface did not typically fail prior to the