Design Method for the Bolts in Bearing-Type Connections with Fillers

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INTRODUCTION

Filler plates are usually used when splicing two members of different depths or thicknesses. The filler plates are usually added to the shallower or thinner member to eliminate the gap between the two connected members, reduce any eccentricity effects, and to create common faying surfaces as well as shear planes between the connected members.

The *Guide to Design Criteria for Bolted and Riveted Joints* (Kulak, Fisher, and Struik, 1987) defines two types of fillers: tight (or developed) and loose (or undeveloped) fillers. Connections with developed or undeveloped fillers can be either slip-critical or bearing-type. The paper presented here will address only the effect of both developed and undeveloped fillers on the shear strength of bolts in bearing-type connections.

Developed fillers are intentionally secured to the main member by additional bolts, such that the fillers act as an integral component of the connected member. The number of additional bolts is determined such that the design stress is uniformly distributed across the combined area of the fillers and the member. Usually, developed fillers are extended beyond the end of the splice plates, and the additional bolts are added to the filler extension outside the main connection. As an alternative, developed fillers can be terminated at the end of the splice plates and the additional bolts placed within the main connection. Figures 1(a) and 1(b) show examples of developed fillers at a bolted girder splice, in which the bolts are placed outside and inside the main connection, respectively.

Conversely, undeveloped fillers serve only as packing pieces and; thus, are assumed to carry no axial load. Undeveloped fillers are terminated at the end of the splice plates and all bolts are placed within the main connection. Connections with undeveloped fillers can fail, by shear failure of the bolts, at a lower load than connections with no fillers (Yura, Hansen, and Frank, 1982). Therefore, additional bolts are usually used to compensate for the reduction in the shear strength of the connection bolts. Figure 1(c) shows an example of an undeveloped filler at a bolted girder splice.

Figure 2 shows the assumed load transfer mechanism for bearing-type connections with fillers. For connections with developed fillers, the load is assumed to be transferred from the main plate to the splice plates through bearing stresses acting on both the bolts and the combined main plate and fillers (developed fillers are assumed to act as an integral component of the connected member), and through bearing stresses acting on both the bolts and the splice plates. These bearing stresses act in opposite directions causing shear stresses, which act through the well-defined shear planes shown in Figure 2(a). Consequently, the shear strength of the bolts in connections with developed fillers can be taken equal to the shear strength of the bolts in connections with no fillers; that is, no reduction in the shear strength of the bolts occurs due to the presence of the developed fillers.

For connections with undeveloped fillers, the load is instead assumed to be transferred from the main plate to the splice plates through bearing stresses acting on both the bolts and the main plate only (undeveloped fillers are assumed to carry no axial load), and through bearing stresses acting in the opposite direction on both the bolts and the splice plates. As shown in Figure 2(b), the shear planes are not clearly defined in this case. Thus, the shear strength of the bolts in connections with undeveloped fillers can be expected to be different than the shear strength of bolts in connections with no fillers.

Three experimental programs have been conducted to investigate the resistance of connections with fillers (Kulak et al., 1987). All three programs investigated the slip resistance of connections with fillers, which is not within the scope of this paper. However, only one program investigated the shear strength of connections with undeveloped fillers, in which the connections failed by shear failure of the bolts (Yura et al., 1982). In that program, it was reported that an increase in the thickness of the undeveloped fillers resulted in increased bending of the bolts, additional deformation of the connection, and reduction in the shear strength of the connection bolts. Based on the findings of that program, an empirical reduction factor for pre-

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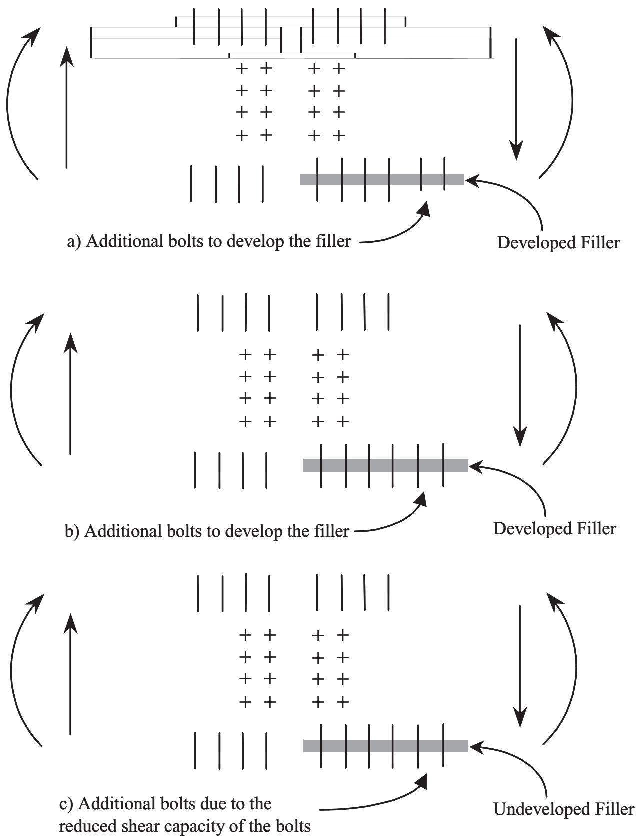

Fig. 1. Bolted girder splice with filler plates.

dicting the reduction in the shear strength of bolts was developed, as shown in the following equation

$$R_b = 1 - 0.4t \tag{1}$$

where t is the total thickness in in., of the fillers assumed to be on one side of the connected plate only. This factor was selected on the basis of a straight line passing through the useful strength experimental data. As defined by Yura et al. (1982), the useful strength is the strength of the connection bolts when restricted by a maximum permitted joint deformation of ¼ in.

The AISC *LRFD Specification* (AISC, 1999) requires that fillers thicker than ¼ in. be extended and that the filler extension be secured by additional bolts to distribute the total stress uniformly across the combined area of the main member and the fillers. The specification also allows these additional bolts to be placed inside the main connection in order to eliminate the need for extending the fillers. As an alternative to extending and developing the fillers, AISC permits the use of undeveloped fillers with thicknesses ranging from ¼ in. to ¾ in., provided that the design shear strength of the bolts is reduced according to the following reduction factor

$$R_b = 1 - 0.4(t - 0.25) \tag{2}$$

This empirical factor, which represents a modified version of the factor reported by Yura et al. (1982), assumes

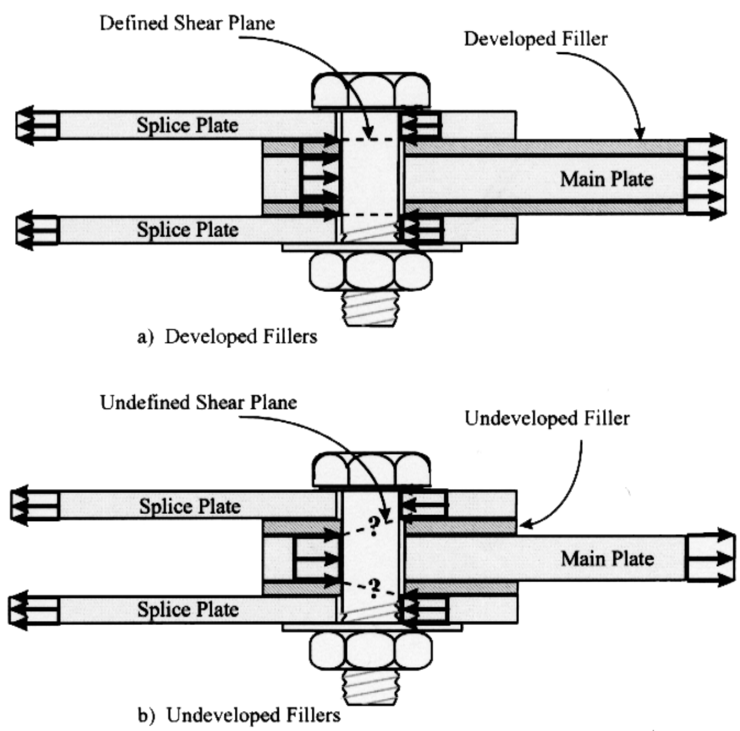

Fig. 2. Load transfer mechanism in connections with fillers.

that fillers less than ¼ in. thick have no effect on the shear strength of the bolts. It also assumes that only the thickness in excess of ¼ in. affects the shear strength of bolts. Although no explanation can be found in the literature for modifying the factor developed by Yura et al. (1982), it is the author's opinion that the reduction factor of Yura et al. was modified to yield results that are close to the experimental results, as controlled by shear failure of the bolts. The strength of the connection bolts as controlled by shear failure of the bolts is defined by Yura et al. as the actual strength of the connection bolts.

Both of the reduction factors (Yura et al., 1982; AISC, 1999) assume that the reduction in the shear strength of bolts is a function of only the thickness of the undeveloped fillers; no consideration is given to the areas of the fillers and the connection plates. These factors were validated for the case in which the fillers and connected plates have the same width. It has not been established whether these factors can be applied to connections that have different filler and connected plate widths. Although many connections are built having equal filler and plate widths, there are cases where the width of the filler can be different than that of the connected plate. An example of such cases is the fillers in a girder flange splice where the flange width for the shallower girder segment is wider than that of the deeper segment. For this case, the filler width is usually narrower than the width of the shallower girder flange.

Further, the two empirical factors (Yura et al., 1982; AISC, 1999) were based on straight-line fitting through the experimental data of connections with undeveloped fillers. Thus, it is questionable whether these factors can be applied when rating connections, in which all bolts are placed within the main connection, not knowing whether the fillers are developed or undeveloped. Figures 1(b) and 1(c) provide examples of such connections. The connections in these figures look identical and; thus, one cannot ascertain whether the fillers are developed or undeveloped.

This paper presents a method for the design of the bolts in bearing-type connections with fillers. The method involves a general reduction factor to be applied to the design shear strength of the bolts. The proposed factor can be used for connections with either developed or undeveloped fillers, thus simplifying the design process by eliminating the need to differentiate between the two types of fillers. The factor is based on a mechanistic model, and takes into account the area of the main connected plate, splice plates, and fillers. The factor is verified by a comparison with the results of the experimental program reported by Yura et al. Finally, two design examples are presented for connections with fillers.

PROPOSED DESIGN METHOD

The proposed method assumes that when all of the bolts are placed within the main connection, the required number of additional bolts is equal for connections with either developed or undeveloped fillers; that is, no distinction is made between developed or undeveloped fillers. A reduction factor for the shear strength of bolts is derived assuming the fillers are developed. The proposed method assumes that the same factor can be used also for undeveloped fillers. This assumption should be satisfactory because a connection cannot identify whether the additional bolts, which are placed within the main connection, were added to develop the fillers or to compensate for the reduced shear strength of bolts due to the presence of undeveloped fillers.

To determine the reduction factor, the required additional number of bolts is first determined such that the design stress is uniformly distributed across the combined area of the fillers and the member. Then, the reduction factor is derived such that it yields the same number of the previously determined additional bolts. This factor is determined as the ratio of the required number of bolts in the absence of the fillers to the total required number of bolts in the presence of developed fillers.

The total number of bolts, N_b, required for connections with developed fillers can be written as

$$N_b = N_{bP} + N_{bf} \tag{3}$$

where

N_{bP} = number of bolts required to resist the factored applied load, P_u, ignoring the effect of the fillers

N_{bf} = number of additional bolts required to develop the fillers

Assuming that the additional bolts pass through all of the connection plates and that the number of shear planes for the additional bolts and for the bolts required to resist the load is equal, Equation 3 can be rewritten as;

$$N_b = \frac{P_u}{\phi r_n} + \frac{P_u}{\phi r_n} \times \frac{A_f}{A_P + A_f} = \frac{P_u}{\phi r_n}\left(1 + \frac{A_f}{A_P + A_f}\right) \tag{4}$$

where

ϕr_n = design shear strength of one bolt

A_f = filler area taken as the sum of areas of the fillers on both sides of the main plate

A_P = area of the connected plates taken as the smaller of either the main plate area, or the sum of the splice plate areas on both sides of the main plate

Defining an amplification factor for the number of bolts, I_b, as the total number of bolts divided by the number of bolts required if the fillers were not present, results in

$$I_b = \frac{1+2\alpha}{1+\alpha} \tag{5}$$

where

$$\alpha = \frac{A_f}{A_P}$$

For the special case where the fillers and the connected plates have identical widths, α can be taken as

$$\frac{t_f}{t_P}$$

where t_f is the total thickness of the filler plates on both sides of the main plate, and t_P is the smaller of either the thickness of the main plate or the total thickness of the splice plates on both sides of the main plate.

To simplify the design of connections with fillers, the total number of connection bolts can be obtained by dividing the design load by a reduced shear strength of the bolts. This reduced strength is defined as the shear strength of the bolts ignoring the effect of the fillers times a reduction factor, R_b, which can be calculated as the inverse of the bolt amplification factor, as follows

$$R_b = \frac{1+\alpha}{1+2\alpha} \tag{6}$$

Equation 6 yields upper and lower limits for the bolt shear strength reduction factor. The factor ranges from 1.0 for the case of no fillers (no additional bolts are needed) to 0.5 for the hypothetical case of an infinitely large filler, with respect to the connected plate. When the fillers become infinitely rigid, the load in the developed fillers becomes equal to the total applied load. Consequently, the number of bolts required to develop the fillers will be equal to that required to transfer the total load from the main member to the fillers. This number of bolts is also equal to the number of bolts required to transfer the load from the fillers to the connection plates. Therefore, when the fillers become infinitely rigid, twice the number of bolts is required (compared to that for connections with no fillers) to transfer the load from the main member to the fillers, and then from the fillers to the connection plates.

COMPARISON WITH TEST RESULTS

As mentioned previously, the proposed factor is derived for connections with developed fillers and assumed applicable to connections with undeveloped fillers. To validate the applicability of the proposed factor to connections with undeveloped fillers, the calculated results are compared with those of the experimental program reported by Yura et al. (1982). The program included two replicate tests of five butt connection specimens having 2-in. thick main plates, and 1-in. thick splice plates. The thickness of the fillers ranged from 0 in., 0.075 in., 0.25 in., 3×0.25 in., to 0.75 in. on each side of the main plate. In all of the specimens, the splice plates, filler plates, and main plates had a 4-in. constant width. The ratio of the grip-to-bolt diameter ranged from 4.6 to 6.1. More details of the experimental program can be found in the paper by Yura et al. (1982).

Figure 3 shows the calculated and experimental effect of the relative fillers-to-connected-plate area on the shear strength reduction factor. Also, Tables 1 and 2 provide a numerical comparison between the calculated and experimental shear strength reduction factors. In the comparison, the filler area is taken as the sum of areas of the fillers on both sides of the main plate. The area of the connected plates is taken as the smaller of either the main plate area, or the sum of the splice plate areas on both sides of the main plate. The experimental reduction factors given in Table 1 are based on the useful shear strength, while those in Table 2 are based on the actual shear strength.

In Table 1, three calculated reduction factors are compared to the useful-strength experimental results; the factor reported by Yura et al. (1982), the factor specified in the AISC *LRFD Specification* (AISC, 1999), and the factor proposed in this paper. In Table 2, only two calculated reduction factors are compared to the actual-strength experimental results; the factor specified in the AISC *LRFD Specification*, and the factor proposed in this paper. The factor reported by Yura et al. is not used in the latter comparison because it was based on the slope of a straight line passing through the useful-strength test results.

Figure 3, Table 1, and Table 2 show that the shear strength of the connection bolts decreases as the ratio of the connected plate area to the filler area increases. When compared to the useful-strength experimental results, the proposed factor produces results that are comparable to those of Yura et al. and are generally better than those of AISC. However, the AISC factor produces results that are generally closer to the actual-strength test results than the proposed factor.

The proposed factor yields conservative estimates of the actual strength of the connections with thick fillers. Nonetheless, as reported by Yura et al., the actual strength of the connections with thick fillers was accompanied by an increase in the joint flexibility and maximum deformation.

It can be argued that joint flexibility is not detrimental to the usefulness of a structure or a structural member. However, to obtain the last 20 percent of the strength for the specimens with the 0.75-in. fillers, the amount of joint deformation had to be doubled and increased from 0.25 in. to an amount in excess of 0.5 in. Further, the concept of

Table 1. Comparison between the Calculated Strength and the Experimental Useful Strength

Spec. #	$\frac{Grip}{d_b}$	$\alpha = A_f / A_P$	Reduction factor				Difference %		
			Test	Proposed	AISC	Yura et al	Proposed	AISC	Yura et al
1	4.6	0	1.033	1.0	1.0	1.0	-3.2	-3.2	-3.2
2	4.6	0	0.972	1.0	1.0	1.0	2.9	2.9	2.9
3	4.7	0.075	0.938	0.935	1.0	0.97	-0.3	6.6	3.4
4	4.7	0.075	0.994	0.935	1.0	0.97	-6.0	0.6	-2.4
5	5.1	0.25	0.903	0.833	1.0	0.9	-7.7	10.7	-0.3
6	5.1	0.25	0.9	0.833	1.0	0.9	-7.4	11.1	0
7	6.3	3×0.25	0.655	0.7	0.8	0.7	6.9	22.1	6.9
8	6.3	3×0.25	0.675	0.7	0.8	0.7	3.7	18.5	3.7
9	6.3	0.75	0.708	0.7	0.8	0.7	-1.1	13.0	-1.1
10	6.3	0.75	0.701	0.7	0.8	0.7	-0.1	14.1	-0.1

Table 2. Comparison between the Calculated Strength and the Experimental Actual Strength

Spec. #	$\alpha = A_f / A_P$	Reduction factor			Difference %	
		Test	Proposed	AISC	Proposed	AISC
1	0	1.033	1.0	1.0	-3.2	-3.2
2	0	0.972	1.0	1.0	2.9	2.9
3	0.075	0.949	0.935	1.0	-1.5	5.4
4	0.075	0.999	0.935	1.0	-6.4	0.1
5	0.25	0.985	0.833	1.0	-15.4	1.5
6	0.25	0.992	0.833	1.0	-16.0	0.8
7	3×0.25	0.856	0.7	0.8	-18.2	-6.5
8	3×0.25	0.87	0.7	0.8	-19.5	-8.0
9	0.75	0.896	0.7	0.8	-21.9	-10.7
10	0.75	0.861	0.7	0.8	-18.7	-7.1

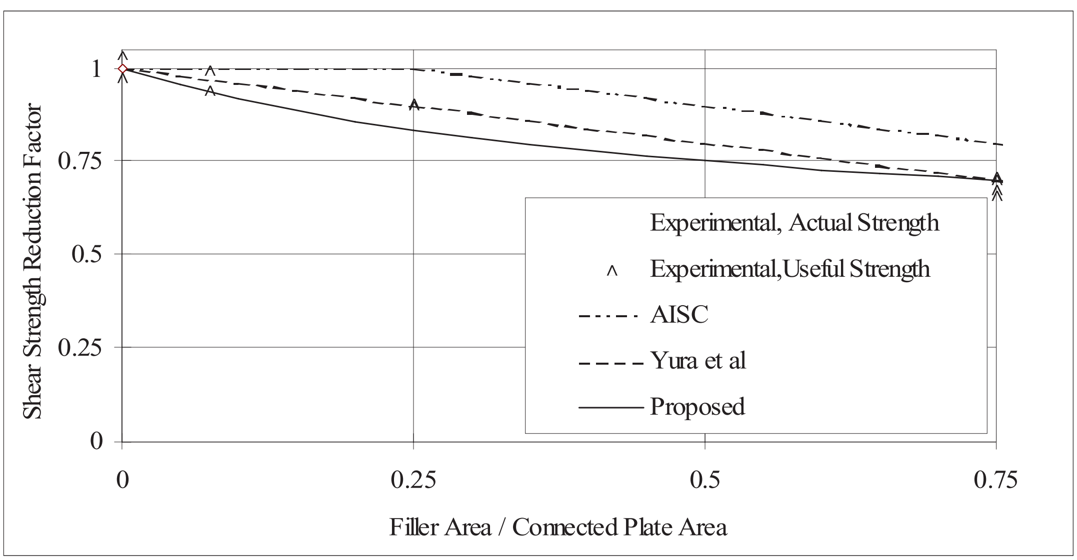

Fig. 3. Effect of relative filler area on the shear strength of connection bolts.

using an upper limit on the permitted joint deformation is not new and is currently used in the design of bolted connections to limit the excessive bearing deformation. Therefore, it is the recommendation of the author that the useful rather than the actual strength be used for the design of connections with fillers to limit the excessive joint deformation caused by the presence of the fillers.

The factors of Yura et al. (1982) and the AISC *LRFD Specification* (1999), which were derived from limited test data, are empirical and take into account only the thickness of the fillers. It is the opinion of the author that the proposed factor provides a more general solution for the prediction of the design shear strength reduction for connections with fillers because it takes into account the area of the fillers, the area of the main connected plate, and the area of the splice plates. It can be argued that the proposed factor is verified by the same limited data from which the current empirical factors were obtained. However, it should be remembered that the current empirical factors were derived from straight-line fitting of limited data; whereas, the proposed factor is derived based on a mechanistic model and it used the limited data only to verify its validity.

The validation of the factor proposed in this paper is limited to the tests reported by Yura et al. (1982). The tests were limited to connections having ⅞-in. diameter bolts, a constant width, and fillers not thicker than 75 percent of the thickness of the main plate. Researchers are advised to experimentally investigate the behavior and strength of connections having variable bolt diameters, variable connection widths, and fillers exceeding 75 percent of the thickness of the main plate. Until more experimental results become available, the proposed factor should provide a satisfactory solution for connections with fillers. The factor can be used regardless of the type of fillers used, provided that all of the bolts are placed within the main connection.

EXAMPLE 1

Given

For the butt splice shown in Figure 4, determine the number of bolts required to resist a factored applied load of 410 kips. Assume that bolt shear controls the strength of the connection. Use ⅞-in. diameter A325-X bolts, ϕr_n = 54.1 kips/bolt.

Solution

Determine the number of bolts required for the side of the connection without fillers:

$$N_b = \frac{P_u}{\phi r_n} = \frac{410}{54.1} = 7.6 \text{ bolts}$$

Determine the number of bolts required for the side of the connection with fillers:

$$N_b = \left(\frac{1+2\alpha}{1+\alpha}\right)\frac{P_u}{\phi r_n} = \left(\frac{1+2\times 1.33}{1+1.33}\right)\times 7.6$$
$$= 1.57 \times 7.6 = 11.9 \text{ bolts}$$

in which $\alpha = \dfrac{t_f}{t_P} = \dfrac{0.5+0.5}{\min.\text{ of}(0.5+0.5,\ 0.75)} = \dfrac{1}{0.75} = 1.33.$

Note that due to the presence of the fillers, the required number of bolts increased by 57 percent.

Therefore, use two transverse rows of four bolts at three in. longitudinal spacing for the side of the connection without fillers (N_b = 8 bolts). Use three transverse rows of four bolts at 3 in. longitudinal spacing for the side of the connection with fillers (N_b = 12 bolts).

EXAMPLE 2

Given

Determine the design strength of the butt splice given in Example 1. Assume that bolt shear controls the strength of the connection and that three transverse rows of four ⅞-in. diameter A325-X bolts are used on each side of the splice, ϕr_n = 54.1 kips/bolt.

Solution

Since the number of bolts is the same for both sides, the side of the connection with filler plates will control the strength of the connection.

The design strength of the connection based on bolt shear is:

$$\phi P_n = N_b \times \left[\left(\frac{1+\alpha}{1+2\alpha}\right)\times \phi r_n\right] = 12 \times (0.636 \times 54.1)$$
$$= 0.636 \times 649.2 = 412.9 \text{ kips}$$

where α = 1.33 as determined in Example 1.

Note that due to the presence of the filler plates, the shear strength of the bolts is reduced by 36.4 percent.

SUMMARY

A method for the design of bolts in bearing-type connections with fillers is presented in this paper. The method involves a general reduction factor to be applied to the design shear strength of the bolts. The factor is based on a mechanistic model, which takes into account the dimensions of all of the connection plates. The proposed method assumes that the required number of additional bolts is

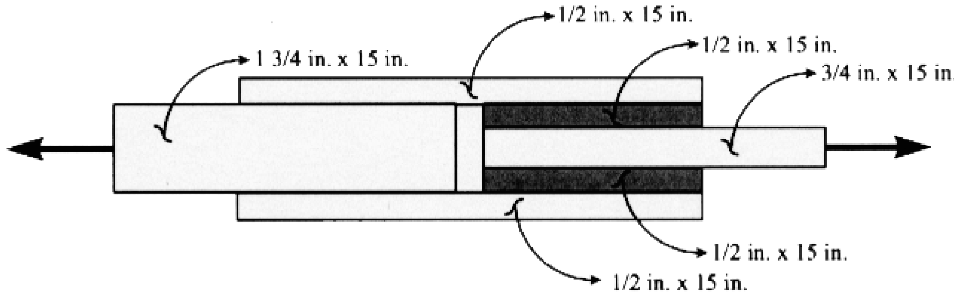

Fig. 4. Connection for Examples 1 and 2.

equal for connections with either developed or undeveloped fillers. Therefore, provided that all of the bolts are placed within the main connection, the proposed factor simplifies the design process since it can be used for connections regardless of the type of fillers used. The factor is determined as the ratio of the required number of bolts in the absence of the fillers to that in the presence of developed fillers. The applicability of the proposed factor to connections with undeveloped fillers is verified by a previous experimental program in which the ratio of the grip-to-bolt-diameter ranged from 4.6 to 6.1, and the ratio of fillers area to main plate area ranged from 0 to 0.75. On average, the proposed factor yields results that are closer to the useful-strength experimental results (which are restricted by a maximum permitted joint deformation of ¼ in.) than the current AISC factor. The AISC factor produces results that are generally closer to the actual-strength test results than the proposed factor. Nonetheless, the actual strength of connections with thick fillers was accompanied by an increase in the joint flexibility and maximum deformation. To obtain the last 20 percent of the strength for the specimens with the 0.75-in. fillers, the amount of joint deformation had to be doubled and increased from 0.25 in. to an amount in excess of 0.5 in. Therefore, it is recommended that the proposed factor be used to limit the excessive deformation for connections with fillers. Finally, to illustrate the use of the proposed factor, two design examples for connections with fillers are presented.

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