Strength and Serviceability of Hanger Connections

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INTRODUCTION

Hanger connections involve bolts in tension due to direct loads and prying action and bending of tee flanges or angle legs. It is the purpose of this paper to show that the analysis method of the latest AISC Manuals, both ASD[1] and LRFD[2] versions, can with minor modification allow for a greatly increased design strength and a more reliable prediction of serviceability loads.

The strength of hanger connections is due mainly to the strength of the bolts but is affected by the bending of the hanger flanges which induces prying action in the bolts. Previous emphasis on this problem has focused on the determination of the actual prying force Q rather than the overall behavior of the connection itself. This paper concentrates on assessing the strength of the connection, both ultimate strength and yield (or separation) strength.

ANALYSIS OF STRENGTH AND SERVICEABILITY

The method for analysis and design of hanger connections currently in use in both the current AISC ASD and LRFD manuals is due to Struik and is presented in Kulak, et al.3 In Ref. 3 the justification for this method is based on its capability to predict the prying force Q with reasonable accuracy. The prediction of Q is important for serviceability because it affects the fatigue life of the connection. The prediction of Q is also important for strength because it reduces the direct load that the bolts can carry. However, for strength, it is most important to know the ultimate load capacity of the hanger connection and the prediction of Q is secondary to this. Thus, for strength, the ultimate capacity calculated by any proposed method of analysis should be compared to tests which give the ultimate or breaking strength of the connection. For serviceability, the analysis method should reasonably predict yield strength so that with a factor of safety (or suitable load and resistance factors) elastic behavior can be reasonably assured.

The following methods are proposed—one for serviceability (yield or separation strength) and the second for strength (ultimate or breaking strength). These are both based on Struik's method as presented in Ref. 3, but they are formulated for efficient calculation and optimum results as presented by Thornton.[4]

For serviceability:

$$\alpha_y' = \frac{1}{\delta(1+\rho)}\left[\frac{4B_y b}{pt^2F_y}\right] \tag{1}$$

$$\text{If } \alpha_y' \le 0,\ T_y = B_y \tag{2}$$

$$\text{If } 0 < \alpha_y' \le 1,\ T_y = \frac{pt^2F_y}{4b}(1+\delta\alpha_y') \tag{3}$$

$$(\text{if } \alpha_y' > 1, \text{ set } \alpha_y' = 1)$$

For strength:

$$\alpha_u' = \frac{1}{\delta(1+\rho)}\left[\frac{4B_u b}{pt^2F_u} - 1\right] \tag{4}$$

$$\text{If } \alpha_u' \le 0,\ T_u = B_u \tag{5}$$

$$\text{If } 0 < \alpha_u' \le 1,\ T_u = \frac{pt^2F_u}{4b}(1+\delta\alpha_u') \tag{6}$$

$$(\text{if } \alpha_u' > 1, \text{ set } \alpha_u' = 1)$$

In the above equations, the notation follows Ref. 1 except as noted in the notation section of this paper.

To test these formulations, the test data produced by Douty and McGuire[5] for T stubs are used. Figure 1 shows the test specimens and Table 1 gives the Douty and McGuire geometric and material data. Table 2 gives the results of applying the above yield and ultimate strength formulation to the specimens of Fig. 1. Table 2 also gives the actual (experimental) yield load, ultimate load, and actual failure mode. In Table 2, $P_y = 4T_y$ and $P_u = 4T_u$, i.e., P_y and P_u are the assembly yield and ultimate strengths which can be compared directly with the actual (experimental) strengths. The parameter α' given by Eq. 1 or Eq. 4, for yield (α_y') or ultimate strength (α_u') respectively, gives an indication of the controlling limit state. If $\alpha' < 0$, the bolts control. If $0 \le \alpha' \le 1$, the bolts and T flange are both controlling. If $\alpha' > 1$, the T flange controls. The "computed failure mode" of Table 2 is based on these ranges of α_u'. Table 3 gives a direct comparison between actual and theoretical results. It can be seen from Tables 2 and 3 that the theory gives excellent agreement with the test results for ultimate strength and generally very good results for yield strength. Some observations on these results can be made. Concerning the ultimate strength results, it is pointed out by Kato and McGuire[6] that after the formation of the collapse mechanism in the T flange (i.e., when the plastic bending stress is F_u at both the bolt line and the stem line) the T stub

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can sustain the load by "hanging action." On the contrary, the post yield strength of the high strength bolts is small and the behavior is less ductile. Thus, in the tests, bolt fracture is usually the failure mode even if the theory indicates that the flange or web will fail first. Nevertheless, the significant deformations of the flange that take place at the P_u load do cause additional load to be placed in the bolts, and this additional load (conventionally called "prying action") does cause the bolts to fracture before their nominal ultimate strength, i.e., $4B_u$, is achieved when the flange is flexible, i.e., $\alpha_u' > 0$.

It will be observed from Tables 2 and 3 that the agreement between experiment and theory for yield is not as good as that for ultimate strength. This occurs because yielding is defined, following Kato and McGuire, as the load at which the bolts first "see" load in addition to the pretension load. This point is also called the "separation point." It is also the load at which a collapse mechanism in the sense of simple plastic theory forms in the T flange. In two instances in Table 2, Kato and McGuire reported that the separation point was not clear (Tests A11 and A15) and no yield load is given. In general, because there is no clear catastrophic failure, the yield load would be much more dependent on small variations in material properties, thickness, initial pretension, and the like. Therefore, it is reasonable to find a bigger variation between theory and experiment here than in the ultimate strength results. On the whole, it is felt that the agreement between theory and experiment for the yield results is very good.

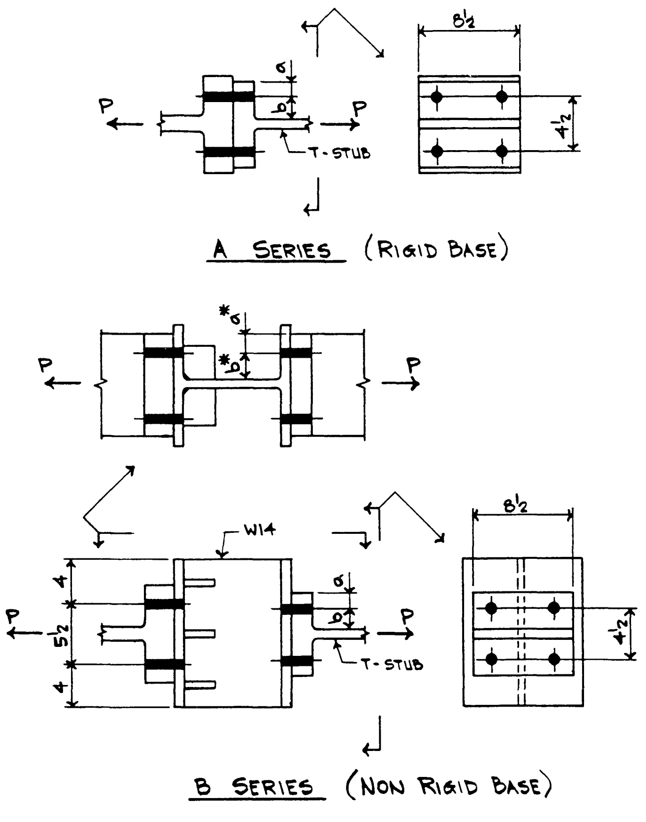

Fig. 1. Test specimens for Douty and McGuire tests.

It should be noted that in the ultimate strength formulation proposed above, the idea for using F_u, the ultimate strength of the T stub material, as the limiting bending stress in the T stub flange, is due to Kato and McGuire.[6] The excellent agreement shown in Table 3 for actual/theoretical ultimate strength validates this idea.

RECOMMENDED DESIGN PROCEDURES

For connection design, the usual factor of safety for ultimate strength and fracture is two in allowable stress design (ASD). In load and resistance factor design, (LRFD) the same level of safety is achieved with a resistance factor of .75 and an expected average load factor of 1.5. Table 4 shows the theoretical ultimate strength $P_u t$ of Table 2 or Table 3 divided by an effective factor of safety of two, and compares this to the actual yield strength $P_y a$ reported by Refs. 5 and 6, also as given and Tables 2 and 3. It can be seen from Table 4 that $P_u t / 2$ is generally within ± 20 percent of the actual yield load $P_y a$ and is usually much closer than this. Therefore, designing for $P_u d = P_u t / 2$ means that at working loads or factored working loads, the connection will have distortions of the same order of magnitude (i.e., 1½ times larger) as elastic distortions, which are vanishingly small for this configuration. For instance, consider Example 31 of the AISC 9th Edition Manual.[1] Considering the WT9×30 flange as a fixed-fixed beam four inches long with a central transverse applied load from the stem, the elastic displacement is 0.0024 in. and the displacement caused by P_y is one and one half times greater at 0.0036 inch. If the gage is increased from 4 in. to 5½-in., the P_y displacement is still only 0.0270 in., or less than 1/32-in. Thus, a suitable design method for strength is the ultimate strength formulation of Eqs. 4, 5, and 6, with an effective average factor of safety of two.

For serviceability, i.e., connections subject to fatigue or where deformations must remain strictly elastic, it is recommended that the yield strength formulation of Eqs. 1, 2, and 3, be utilized with the same effective factor of safety of two. Table 3, as noted before, shows that $P_y a / P_y t$ is reasonably close to one, given the difficulties attendant to identifying yield or separation. There is reasonably certainty that with a factor of safety of two, Eqs. 1–3 will result in a connection configuration which will remain essentially elastic at service loads, because the elastic load $P_c t = P_y t / 1.5$ is greater than the design load $P_y d = P_y t / 2$.

SUMMARY

The recommended serviceability design method is somewhat more conservative than that now used in both the ASD and LRFD AISC Manuals in that bolt yield strength rather than bolt tensile strength is used, but the recommended method for strength, which is justified by comparison to actual test data, can result in much more economical connections because

Table 1.
Douty and McGuire *T*-Stub Tests—Data (from Refs. 5 and 6)

Test No.	*T*-Stub		Base		Bolt Dia.	Geometric Parameters					Bolt Strength		*T*-Stub Strength	
											Yield	Ultimate	Yield	Ultimate
	t_f (in.)	t_w (in.)	t_f (in.)	t_w (in.)	d (in.)	a (in.)	b (in.)	a' (in.)	b' (in.)	ρ	B_y (kips)	B_u (kips)	F_y (ksi)	F_u (ksi)
A1	0.751	0.438	Rigid	Rigid	⅞	1.50	2.43	1.94	1.59	0.82	37.40	56.0	34.5	60–75
A3	1.680	0.945	Rigid	Rigid	⅞	1.50	1.78	1.94	1.34	0.69	37.40	62.0	26.0	60–75
A4	2.000	1.000	Rigid	Rigid	⅞	1.50	1.75	1.94	1.31	0.68	37.40	59.0	31.1	60–75
A5	0.751	0.438	Rigid	Rigid	1⅛	1.50	2.03	2.06	1.47	0.71	58.75	102.0	33.3	60–75
A7	1.680	0.945	Rigid	Rigid	1⅛	1.50	1.78	2.06	1.22	0.59	58.75	102.0	27.0	60–75
A8	2.500	1.000	Rigid	Rigid	1⅛	1.50	1.75	2.06	1.19	0.58	58.75	105.7	31.0	60–75
A9	0.751	0.438	Rigid	Rigid	⅞	1.75	2.03	2.19	1.59	0.73	37.40	56.0	34.5	60–75
A10	1.102	0.625	Rigid	Rigid	⅞	1.66	1.94	2.10	1.50	0.72	37.40	61.0	31.1	60–75
A11	1.680	0.945	Rigid	Rigid	⅞	1.75	1.78	2.19	1.34	0.61	37.40	61.7	26.0	60–75
A12	2.000	1.000	Rigid	Rigid	⅞	1.75	1.75	2.19	1.31	0.60	37.40	59.7	31.1	60–75
A13	0.751	0.438	Rigid	Rigid	1⅛	1.75	2.03	2.31	1.47	0.64	58.75	101.0	33.3	60–75
A14	1.102	0.625	Rigid	Rigid	1⅛	1.66	1.94	2.22	1.38	0.62	58.75	97.0	29.5	60–75
A15	1.680	0.945	Rigid	Rigid	1⅛	1.75	1.78	2.31	1.22	0.53	58.75	100.0	27.0	60–75
A16	2.500	1.000	Rigid	Rigid	1⅛	1.75	1.75	2.31	1.19	0.51	58.70	106.0	31.0	60–75
B1	0.751	0.438	1.128	0.695	⅞	1.50	2.03	1.94	1.59	0.82	37.40	64.0	34.5	60–75
B3	1.102	0.625	1.128	0.695	⅞	1.66	1.94	2.10	1.50	0.72	37.40	62.0	31.1	60–75
B4	1.102	0.625	2.093	1.310	⅞	1.66	1.94	2.10	1.50	0.72	37.40	60.0	31.1	60–75
B5	1.102	0.625	3.033	1.875	⅞	1.66	1.94	2.10	1.50	0.72	37.40	60.0	31.1	60–75
B6	1.680	0.945	1.128	0.695	⅞	1.50*	2.40*	1.94*	1.96*	1.01*	37.40	60.0	33.0*	60–75
B7	1.680	0.945	2.093	1.310	⅞	1.50	1.78	1.94	1.34	0.69	37.40	55.5	26.0	60–75
B9	1.680	0.945	1.128	0.695	1⅛	1.50*	2.40*	2.06*	1.24*	0.89*	58.75	97.0	33.0*	60–75
B10	1.680	0.945	2.093	1.310	1⅛	1.50	1.78	2.06	1.22	0.59	58.75	99.0	27.0	60–75
B12	2.500	1.000	1.128	0.695	1⅛	1.50*	2.40*	2.06*	1.84	0.89*	58.75	100.0	33.0*	60–75
B13	2.500	1.000	2.093	1.310	1⅛	1.50	1.75	2.06	1.14	0.58	58.75	99.4	31.0	60–75

* Indicates data based on non-rigid base.

capacity is increased up to F_u / F_y (61 percent for A36 steel) when $\alpha_u' > 1$.

NOTATION

B_u = Bolt tensile strength, ksi

B_y = Bolt yield strength, ksi

F_u = *T*-flange tensile strength, ksi

F_y = *T*-flange yield strength, ksi

P_u = Test specimen ultimate strength (= $4T_u$), kips

P_y = Test specimen yield (separation) strength (= $4T_y$), kips

T_u = External force at which *T* flange tributary to one bolt attains ultimate strength state, kips

T_y = External force at which *T*-flange tributary to one bolt yields or separates, kips

Superscripts

a = actual (experimental)

d = design

t = theoretical

Subscripts

e = elastic

u = ultimate

y = yield or separation

REFERENCES

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2. American Institute of Steel Construction, *Manual of Steel*

Table 2.
Douty and McGuire *T*-Stub Tests—Theoretical and Actual Results (from Refs. 5 and 6)

	Computed Strength (Theoretical)								Actual Strength (Experimental)			
	Bolts and Flange						Web					
	Yield			Ultimate			Yield	Ultimate	Yield	Ultimate		
Test No.	α_y	T_y (kips)	P_y (kips)	α_u	T_u (kips)	P_u (kips)	P_y (kips)	P_u (kips)	P_y (kips)	P_u (kips)	Computed Failure Mode	Actual Failure Mode
A1	1.32	23.10	92.5	1.04, .69	40.2–43.5	161–174	128	273–279	88	176	Flange, Bolts	Bolt Fracture
A3	–.27	37.40	150.0	–.47, –.48	62.0	248	209	482–602	136	256	Bolts	Bolt Fracture
A4	–.48	37.40	150.0	–.53, –.58	59.0	236	264	510–638	140	219	Bolts	Nut Stripping
A5	2.70	23.40	93.4	2.57, 1.89	52.6–65.8	168–210	124	223–279	108	224	Flange	Flange
A7	–.10	58.75	235.0	–.27, –.39	102.0	408	217	482–602	180	392	Bolts	Bolt Fracture
A8	–.58	58.75	235.0	–.60, –.66	105.7	423	263	510–638	240	>404	Bolts	Did Not Fail[4]
A9	1.39	23.10	92.5	1.09, .73	40.2–44.3	161–177	128	223–279	96	177	Flange, Bolts	Bolt Fracture
A10	.30	32.90	132.0	.14, –.04	57.1–61.0	228–244	165	319–398	112	240	Bolts, Flange	Bolt Fracture
A11	–.28	37.40	150.0	–.43, –.50	67.1	247	209	482–602	—[5]	256	Bolts	Bolt Fracture
A12	–.50	37.40	150.0	–.56, –.60	59.7	239	264	510–638	140	245	Bolts	Bolt Fracture
A13	2.82	23.40	93.4	2.65, 1.95	52.6–65.8	168–210	124	223–279	108	228	Flange	Web
A14	.97	46.80	187.0	.62, .33	81.4–86.7	325–345	157	319–398	140	286[3]	Flange, Bolts, Web	Web[3]
A15	–.01	58.75	235.0	–.27, –.42	100.0	400	217	482–602	—[5]	404	Bolts	Bolt Fracture
A16	–.61	58.75	235.0	–.63, –.69	106.0	424	263	510–638	240	>404	Bolts	Did Not Fail[4]
B1	1.32	23.10	92.5	1.29, .89	40.2–47.9	161–192	128	223–279	100	202	Flange, Bolts	Bolt Fracture
B3	.51*	29.00*	116.0*	.15, –.03	57.6–62.0	231–248	165	319–398	93[6]	230	Bolts, Flange	Bolt Fracture
B4	.29	32.90	132.0	.12, –.05	56.5–60.0	226–240	165	319–398	96	228	Bolts, Flange	Bolt Fracture
B5	.29	32.90	132.0	.12, –.05	56.5–60.0	226–240	165	319–398	120	230	Bolts, Flange	Bolt Fracture
B6	.51*	28.70*	115.0*	–.05*,–.16*	60.0	240	209[1]	482–602	100	254	Bolts	Bolt Fracture
B7	–.27	37.40	150.0	–.44, –.59	55.5	222	209	482–602	—	233	Bolts	Bolt Fracture
B9	1.35*	39.00*	156.0*	.25*, .07*	84.4*–92.5*	338*–370*	219[1]	482–602	140	348	Bolts, Flange	Bolt Fracture
B10	–.10	58.75	235.0	–.29, –.40	99.0	396	217	482–602	220	403	Bolts	Bolt Fracture
B12	1.35*	39.00*	156.0*	.28*, .09*	86.2*–94.0*	345*–376*	264[2]	510–638	160	378	Bolts, Flange	Bolt Fracture
B13	–.58	58.75	235.0	–.62, –.67	99.4	398	264	510–638	216	>404	Bolts	Did Not Fail

1. Based on F_y= 26.0 in *T* stub.
2. Based on F_y= 31.0 in *T* stub.
3. Imperfection in material.
4. Exceeded machine capacity of 404 kips.
5. No abrupt increase bolt tension. Separation point (yield point) is not clear.
6. Estimated from Fig. 7 of Ref. 5.

* Indicates data based on non-rigid base.

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Table 3.
Comparison of Actual and Theoretical Results

Test No.	Yield Strength			Ultimate Strength		
	Actual $P_y a$ (kips)	Theoretical $P_y t$ (kips)	Actual/Theoretical $P_y a / P_y t$	Actual $P_u a$ (kips)	Theoretical $P_u t$ (kips)	Actual/Theoretical $P_u a / P_u t$
A1	88	92.5	.95	176	168	1.05
A3	136	150.0	.91	256	248	1.03
A4	140	150.0	.93	219	236	.93
A5	108	93.4	1.16	224	189	1.19
A7	180	217.0	.83	392	408	.96
A8	240	235.0	1.02	>404	423	
A9	96	92.5	1.04	177	169	1.05
A10	112	132.0	.85	240	236	1.02
A11	—	150.0		256	247	1.04
A12	140	150.0	.93	245	239	1.03
A13	108	93.4	1.16	228	189	1.21
A14	140	157.0	.89	286	335	.80
A15	—	217.0		404	400	1.01
A16	240	235.0	1.02	>404	424	
B1	100	92.5	1.08	202	177	1.14
B3	93	116.0	.80	230	240	.96
B4	96	132.0	.73	228	233	.98
B5	120	132.0	.91	230	233	.99
B6	100	115.0	.87	254	240	1.06
B7	—	150.0		233	222	1.05
B9	140	156.0	.90	348	354	.98
B10	220	217.0	1.01	403	396	1.02
B12	160	156.0	1.03	378	361	1.05
B13	216	235.0	.92	>404	398	

Table 4.
Comparison of Ultimate Strength Design Values with Actual Yield Strength Values

Test No.	$P_u^d = \frac{P_u^t}{2}$ (kips)	$P_y a$ (kips)	$\frac{P_y a}{P_u d}$
A1	84.0	88	1.05
A3	124.0	136	1.10
A4	118.0	140	1.19
A5	94.5	108	1.14
A7	204.0	180	.88
A8	212.0	240	1.13
A9	84.5	96	1.14
A10	118.0	112	.95
A11	124.0	—	—
A12	120.0	140	1.17
A13	94.5	108	1.14
A14	168.0	140	.83
A15	200.0	—	—
A16	212.0	240	1.13
B1	88.5	100	1.13
B3	120.0	93	.78
B4	117.0	96	.82
B5	117.0	120	1.03
B6	120.0	100	.83
B7	111.0	—	—
B9	177.0	140	.79
B10	198.0	220	1.11
B12	181.0	160	.88
B13	199.0	216	1.08