武漢大學
WUHAN UNIVERSITY

STAINLESS STEEL IN STRUCTURES
FIFTH INTERNATIONAL EXPERTS SEMINAR
LONDON, UK. 18-19 SEPTEMBER 2017

Experimental Behaviour of Stainless Steel Bolted T-stub Connections under Monotonic Loading

Huanxin Yuan*, S. Hu, X.X. Du, L. Yang, X.Y. Cheng, Y.S. Du

PhD, Associate Professor in Structural Engineering
Email: yuanhx@whu.edu.cn
School of Civil Engineering,
Wuhan University, Wuhan 430072, China

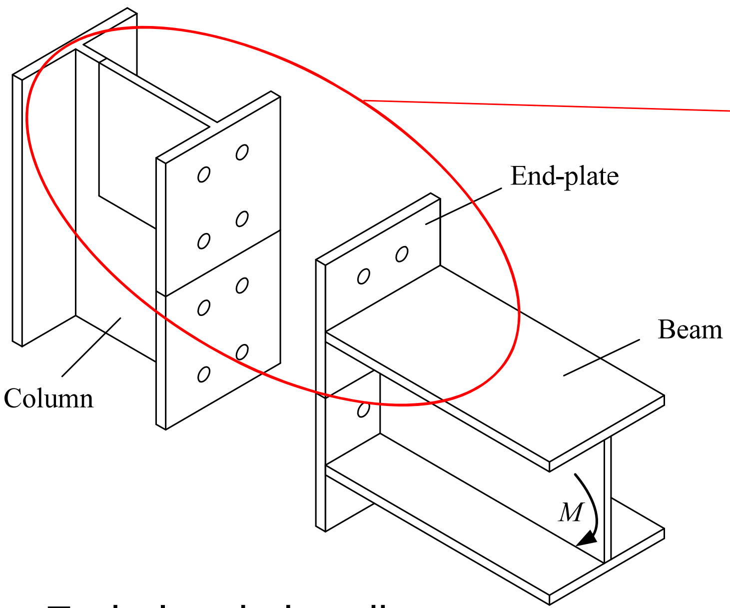
CONTENTS

Introduction

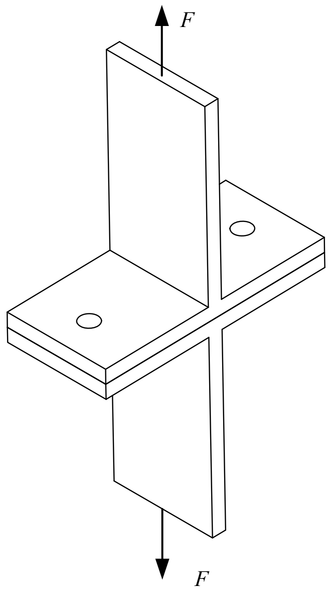
◎ Equivalent T-stub in tension

Basic components

- Column flange in bending
- End-plate in bending
- Flange cleat in bending
- Base plate in bending under tension



End-plate in bending



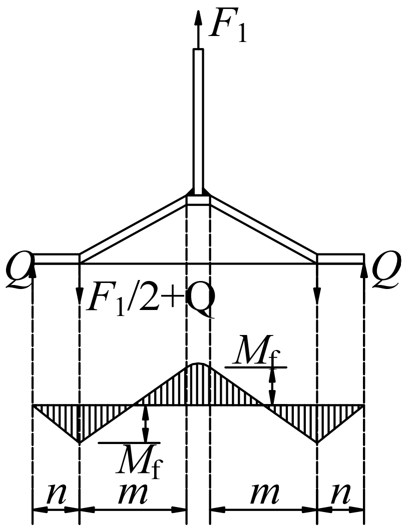
T-stub

Introduction

◎ Ultimate behaviour of bolted T-stubs

Parameter $\beta_u = \dfrac{2M_f}{F_t m}$

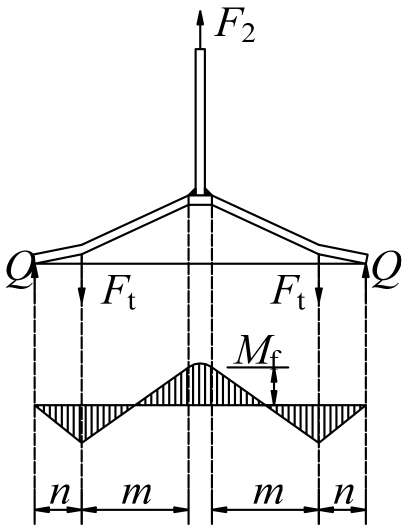
Both the flexural strength of the flange and the tensile strength of the bolt contributed to the tension resistance and failure mechanism



Type-1

complete yielding of the flange plate

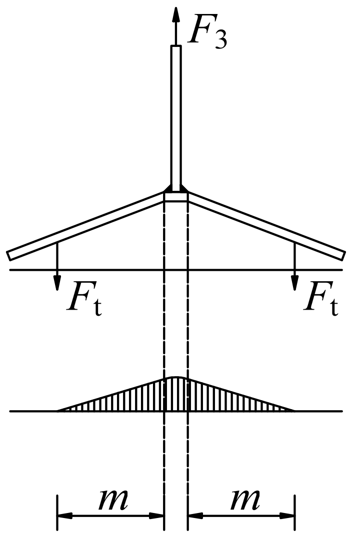
$\beta_u \le \beta_{u,lim}$



Type-2

development of two hinges together with bolt failure

$\beta_{u,lim} \le \beta_u \le 2$



Type-3

bolt failure only

$\beta_u > 2$

Introduction

◎ **Existing studies on bolted T-stub connections**

A series of theoretical and experimental studies have been carried out to explore the behaviour of bolted T-stub connections.

- **Piluso et al. (2001a, b)** — Theoretical model and experimental validation
- **Coelho et al. (2004, 2006)** — Experimental and numerical studies
- **Piluso and Rizzano (2008)** — Cyclic loading tests
- **Massimo et al. (2014)** — T-stubs with four bolts per row

Carbon steel

- **Zhao et al. (2016)**
  Chen et al. (2017) — Tests on high strength steel T-stub joints
- **De Matteis et al. (2014)** — Aluminium T-stub joints

Introduction

◎ **Stainless steel versus carbon steel**

- Prominent corrosion resistance
- Favourable architectural appearance
- Fundamental differences in material properties

The material nonlinearity and strain hardening may result in significant changes of the load-carrying behaviour of bolted T-stub connections.

Bouchaïr et al. (2008) conducted numerical studies on stainless steel T-stub joints by considering the prying effects.

Publically reported experiments on stainless steel bolted T-stub connections are scarce.

T-stub test specimens

◎ Specimens geometry

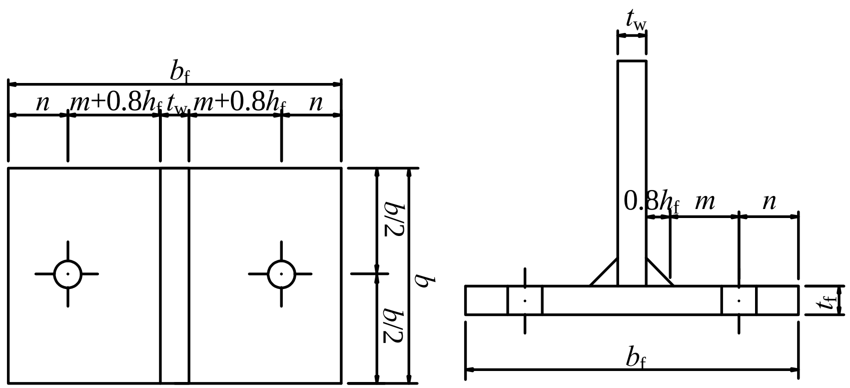
A total of 27 stainless steel bolted T-stubs with various geometric configurations

- Two stainless steel grades (EN 1.4301 and EN 1.4462)
- Two types of stainless steel bolts (A4-70 and A4-80)
- Two plate thicknesses (8 mm and 12 mm)
- Two bolt diameters (12 mm and 16 mm)
- Three configurations of bolts (one bolt, two bolts and four bolts per row)
- Two conditions of bolts (preloaded and snug tight)

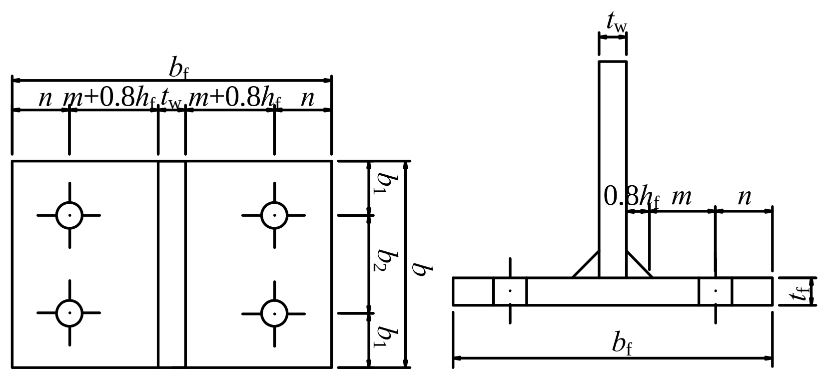
T-stub test specimens

◎ **Specimens geometry**

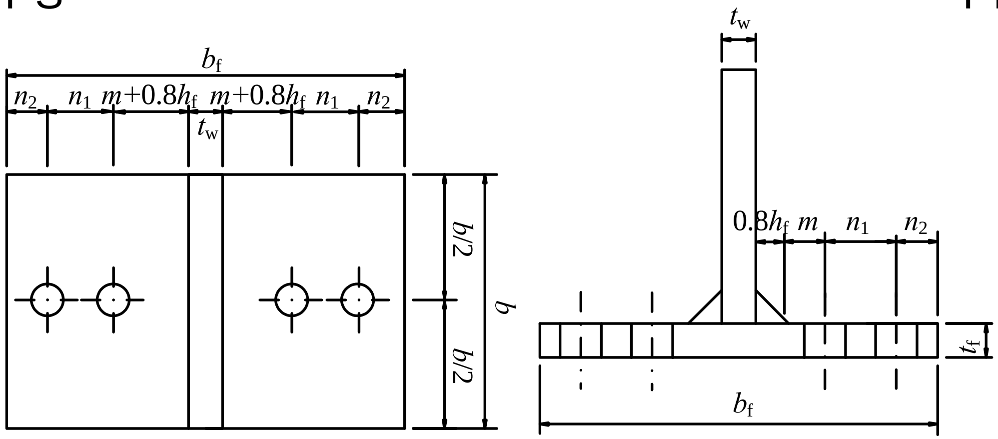
The specimens are denoted as T-S, T-D and T-F:



T-S



T-D



T-F

T-stub test specimens

◎ Specimens geometry

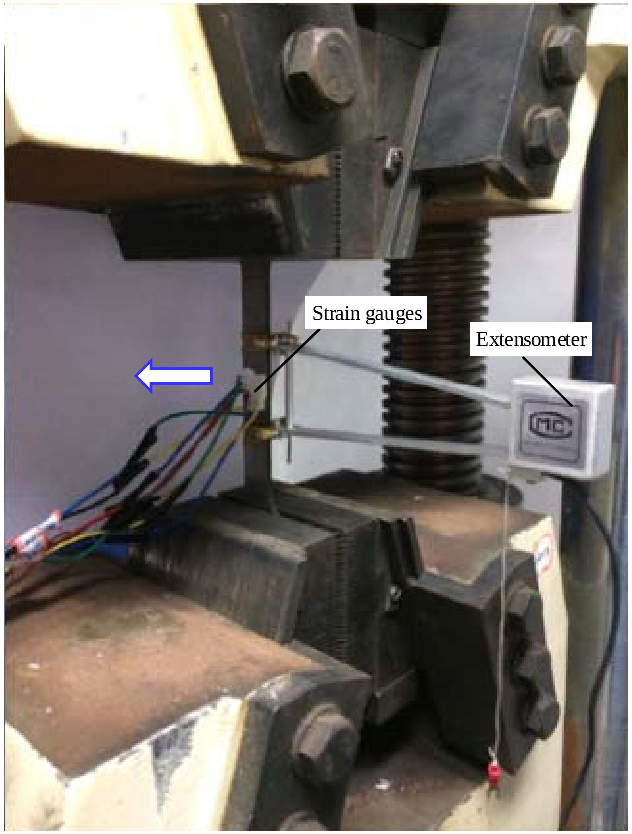
Type	Specimen	Material	Bolt	d_b	n_1	n_2	n	m	b_1	b_2	b	b_f	$t_f = t_w$	h_f	Bolt preload (kN)
T-S	S1	EN 1.4301	A4-70	16	-	-	50	50.2	-	-	120	222	11.85	6	59.1
	S2	EN 1.4301	A4-80	12	-	-	35	65.2	-	-	120	222	11.85	6	27.5
	S3	EN 1.4462	A4-80	16	-	-	50	50.2	-	-	90	222	12.58	6	58.3
	S4	EN 1.4462	A4-80	12	-	-	50	53.0	-	-	120	222	7.72	5	21.3
	S5	EN 1.4462	A4-80	16	-	-	50	53.0	-	-	90	222	7.72	5	59.1
	S6	EN 1.4301	A4-80	12	-	-	50	53.0	-	-	120	222	7.85	5	30.6
	S7	EN 1.4462	A4-80	16	-	-	50	53.0	-	-	120	222	7.72	5	56.9
	S8	EN 1.4301	A4-70	16	-	-	50	50.2	-	-	90	222	11.85	6	56.2
	S9	EN 1.4301	A4-80	12	-	-	35	65.2	-	-	120	222	11.85	6	1.3
T-D	D1	EN 1.4301	A4-70	16	-	-	50	50.2	40	70	150	222	11.85	6	44.3
	D2	EN 1.4301	A4-80	12	-	-	35	65.2	40	70	150	222	11.85	6	29.1
	D3	EN 1.4462	A4-70	16	-	-	35	68.0	40	70	150	222	7.72	5	53.1
	D4	EN 1.4462	A4-70	16	-	-	35	65.2	40	70	150	222	12.58	6	48.0
	D5	EN 1.4462	A4-70	16	-	-	50	50.2	40	70	150	222	12.58	6	45.2
	D6	EN 1.4301	A4-80	16	-	-	35	65.2	40	70	150	222	11.85	6	45.8
	D7	EN 1.4301	A4-80	12	-	-	35	65.2	28	54	110	222	11.85	6	29.4
	D8	EN 1.4301	A4-80	12	-	-	35	65.2	40	70	150	222	11.85	6	1.8
T-F	F1	EN 1.4301	A4-70	12	50	30	80	73.0	-	-	120	322	7.85	5	23.7
	F2	EN 1.4301	A4-70	16	50	30	80	70.2	-	-	90	322	11.85	6	36.8
	F3	EN 1.4301	A4-80	12	40	70	110	40.2	-	-	90	322	11.85	6	23.5
	F4	EN 1.4462	A4-80	16	50	30	80	70.2	-	-	120	322	12.58	6	39.6
	F5	EN 1.4462	A4-80	12	50	30	80	73.0	-	-	90	322	7.72	5	29.3
	F6	EN 1.4301	A4-70	12	50	30	80	70.2	-	-	120	322	11.85	6	23.9
	F7	EN 1.4301	A4-80	16	50	30	80	70.2	-	-	120	322	11.85	6	34.7
	F8	EN 1.4301	A4-70	12	50	30	80	70.2	-	-	90	322	11.85	6	25.8
	F9	EN 1.4462	A4-80	12	50	30	80	73.0	-	-	120	322	7.72	5	27.9
	F10	EN 1.4301	A4-80	12	40	70	110	40.2	-	-	90	322	11.85	6	1.5

All dimensions except the preload are in mm.

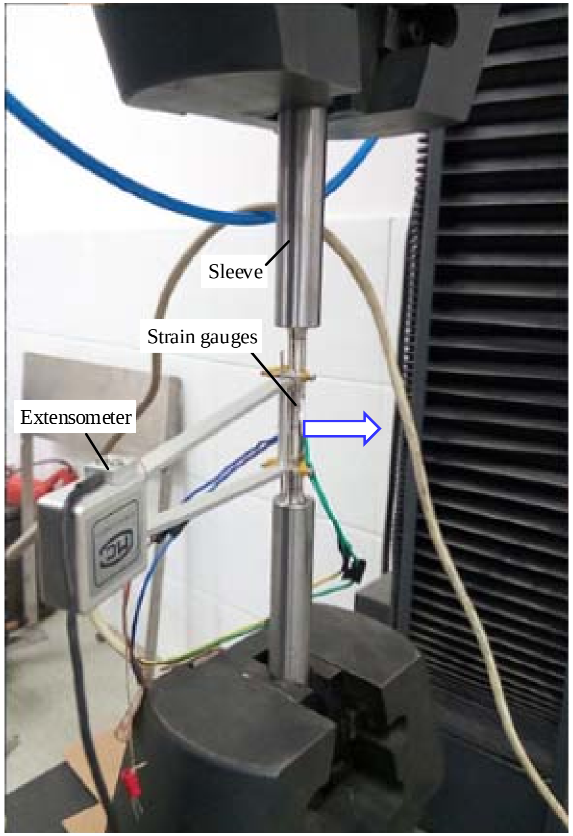
T-stub test specimens

◎ **Material properties**

A total of 12 rectangular tensile coupons (plates) and 12 round tensile coupons (bolts)



Rectangular tensile coupons

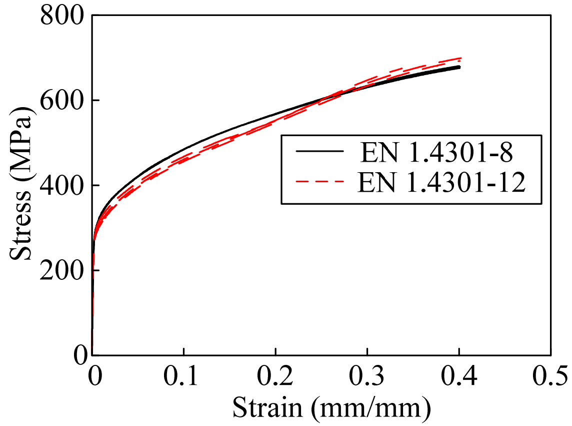


Round tensile coupons

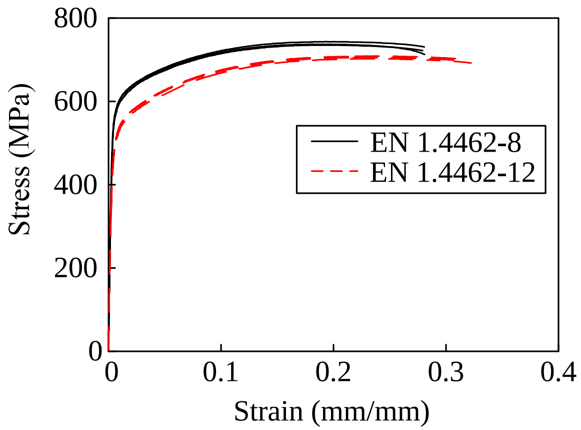
T-stub test specimens

◎ Material properties

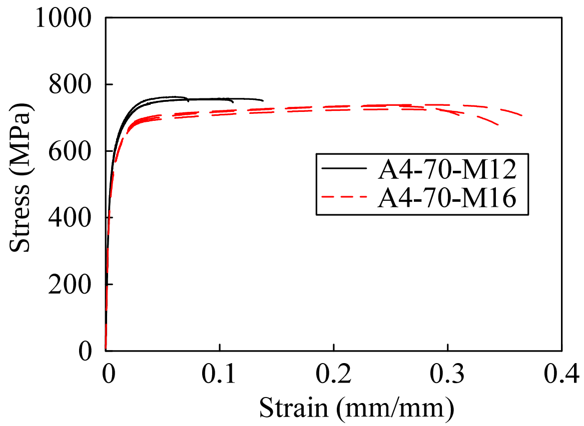
Stress-strain curves of the stainless steel plates and bolts：



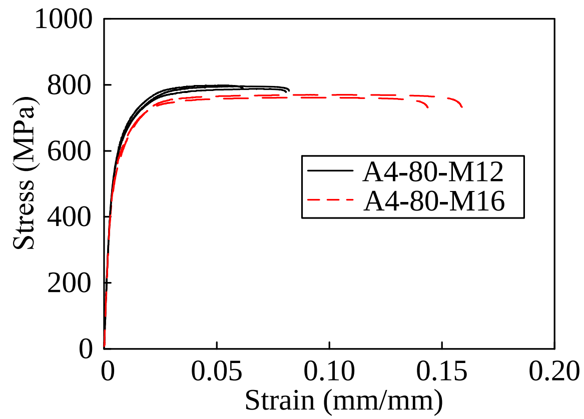
EN 1.4301 plates



EN 1.4462 plates



A4-70 bolts



A4-80 bolts

T-stub test specimens

◎ Material properties

Measured material properties of stainless steel plates and bolts

Stainless steel plates and bolts	Plate thickness or nominal bolt diameter (mm)	v	E_0 (MPa)	$\sigma_{0.01}$ (MPa)	$\sigma_{0.2}$ (MPa)	$\sigma_{1.0}$ (MPa)	σ_u (MPa)	ε_u (%)	ε_f (%)	n
EN 1.4301	7.85	0.257	180700	191.4	291.7	338.9	706.0	-	62.9	7.1
EN 1.4301	11.85	0.258	182800	184.7	280.4	319.1	719.6	-	57.7	7.2
EN 1.4462	7.72	0.207	188700	296.5	551.4	614.5	738.4	19.3	33.0	4.8
EN 1.4462	12.58	0.226	184000	227.8	464.6	552.8	705.3	23.3	37.4	4.2
A4-70	12	-	175400	273.8	522.6	667.1	758.1	8.5	36.5	4.6
A4-70	16	-	173000	283.8	484.6	622.7	732.7	26.0	44.9	5.6
A4-80	12	-	184500	271.5	553.9	710.4	794.0	5.9	29.7	4.2
A4-80	16	-	175300	300.7	524.4	682.3	765.4	9.8	33.4	5.4

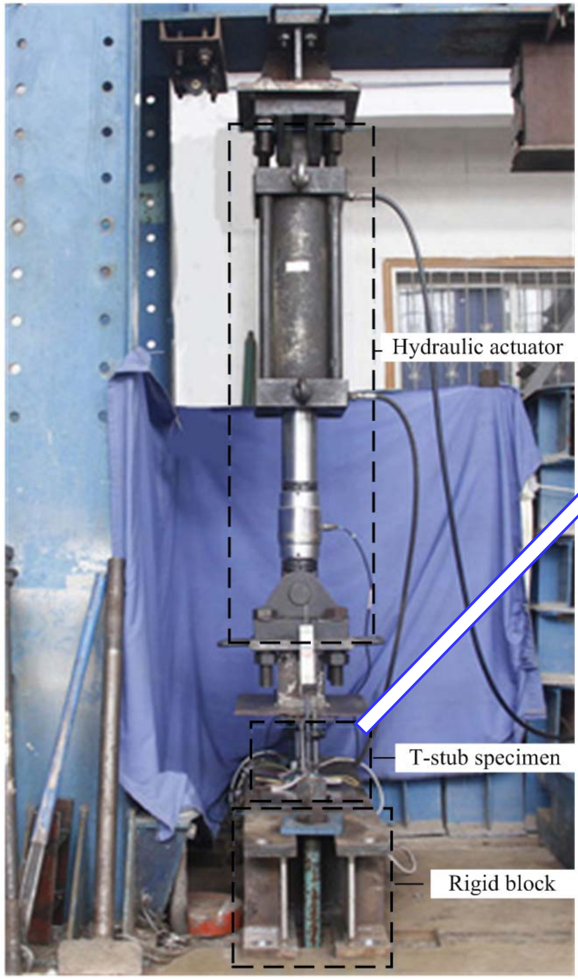
- EN 1.4301 versus EN 1.4462

  lower nominal yield strength and more pronounced strain hardening capacity

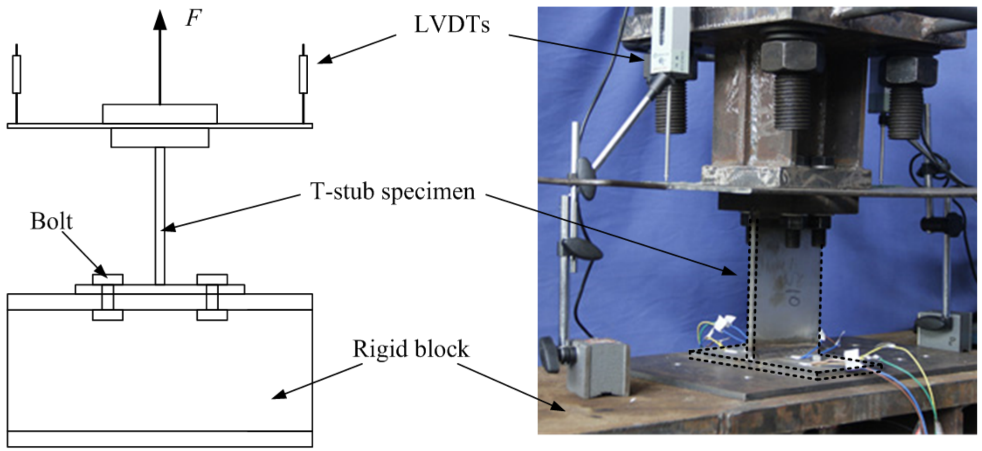
- Stainless steel bolts compared with plates

  less considerable strain hardening capacities

Monotonic loading tests



Test setup

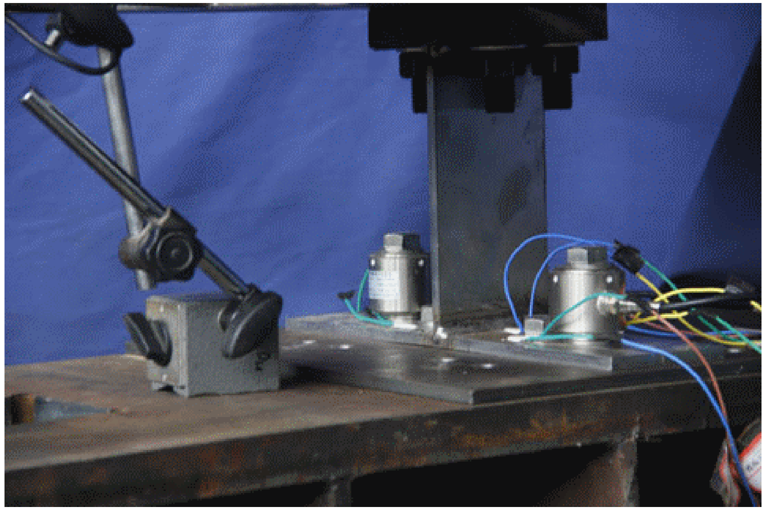


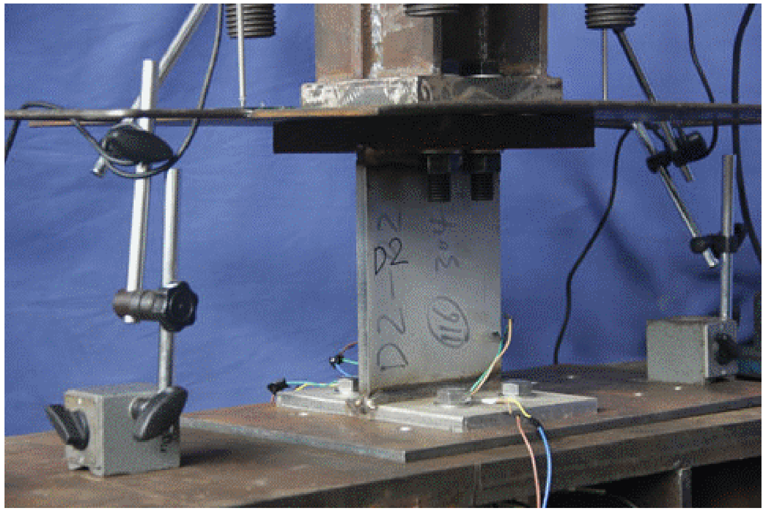
- 600 kN hydraulic actuator with electrohydraulic servo controlling system
- Two symmetrically LVDTs
- Six (four) strain gauges
- Displacement control

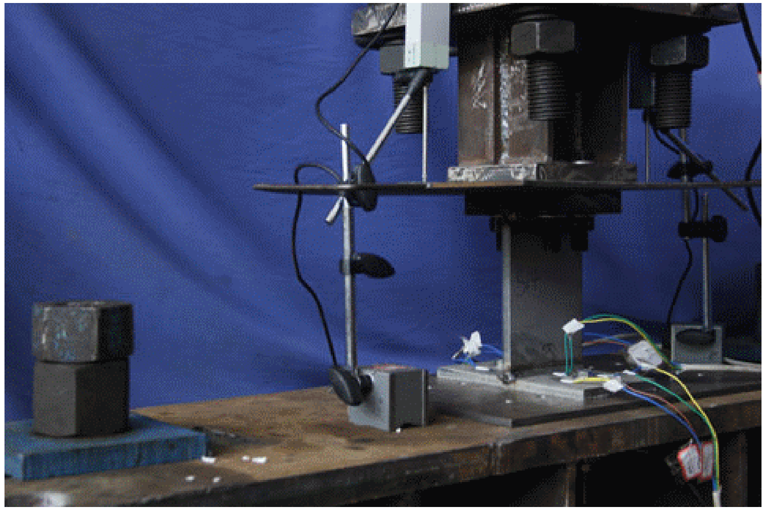
linear stage: 0.5 mm/min; plastic stage: 1.0 mm/min

Monotonic loading tests

Loading process



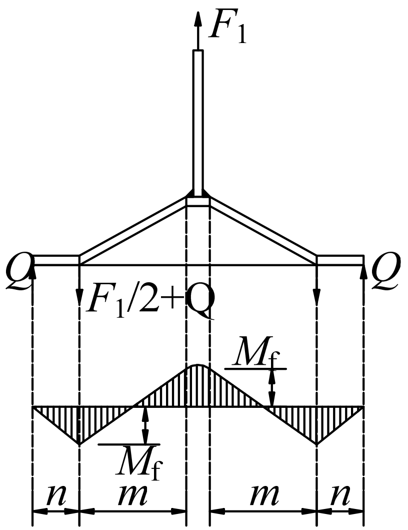




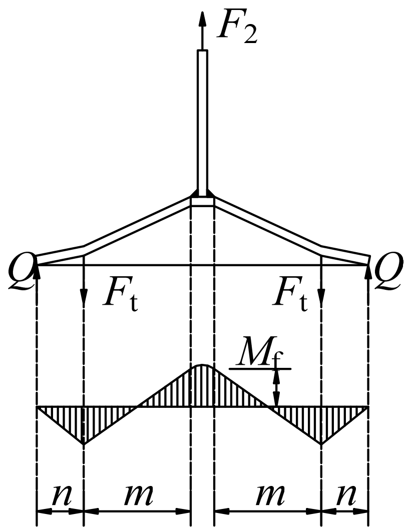
Discussion of experimental results

◎ **Failure modes**

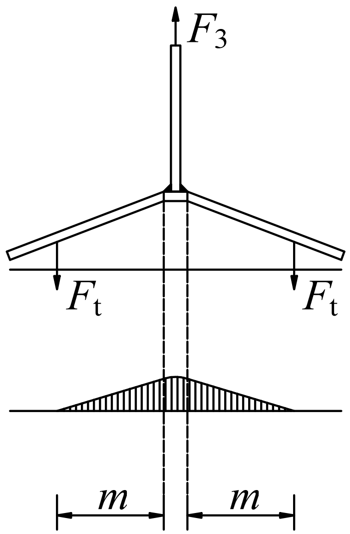
Three typical failure modes:



Type-1



Type-2



Type-3

complete yielding of the flange plate

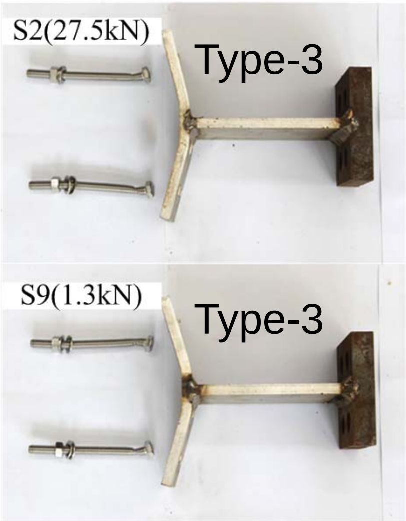
development of two hinges together with bolt failure

bolt failure only

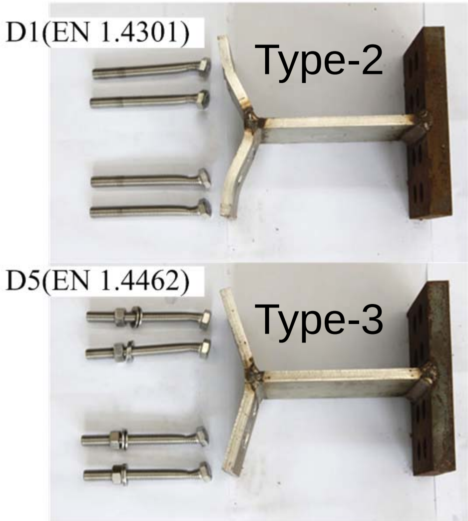
Discussion of experimental results

◎ Failure modes

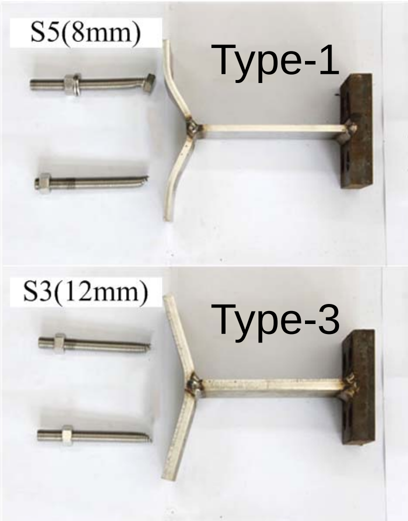
- Bolt preload has little effect on the failure mode
- Material grade, flange thickness and bolt diameter results in changes of the failure modes
- The bolt shear failure can be observed due to the presence of the connected rigid support



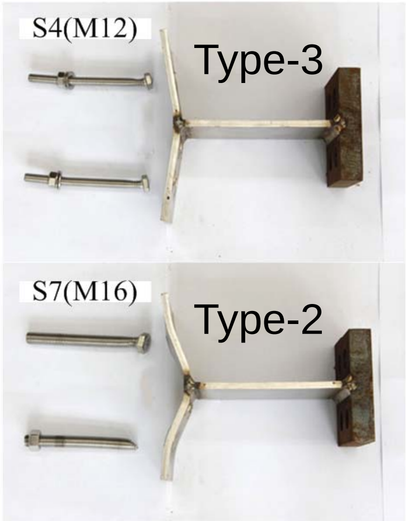
Bolt preload



Flange material



Flange thickness



Bolt diameter

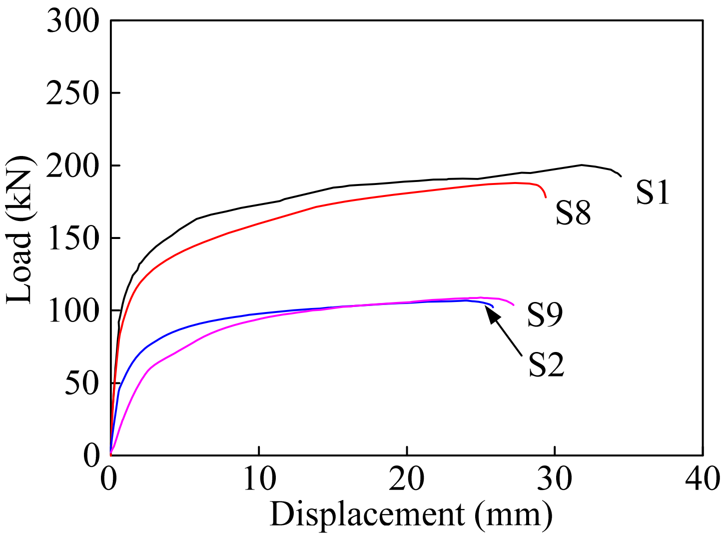
Discussion of experimental results

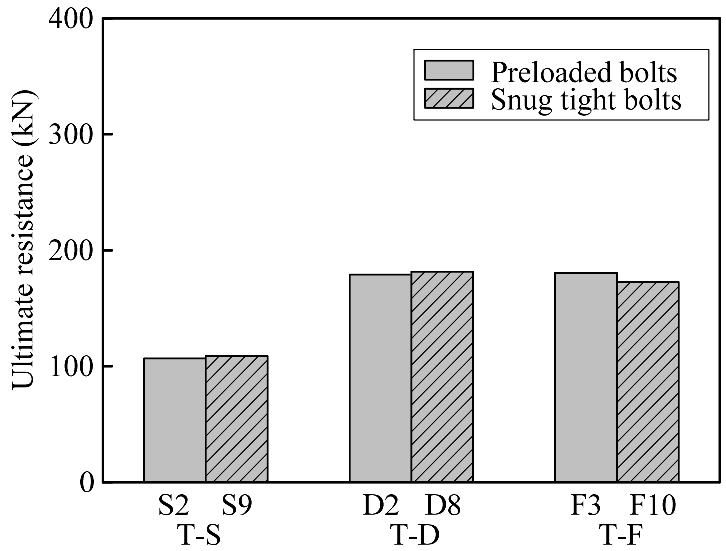
◎ Load-carrying behaviour

- **Bolt preloading (S2, 27.5 kN vs. S9, 1.3 kN)**

  significantly increased initial stiffness

  little effect on the ultimate resistance and deformation capacity





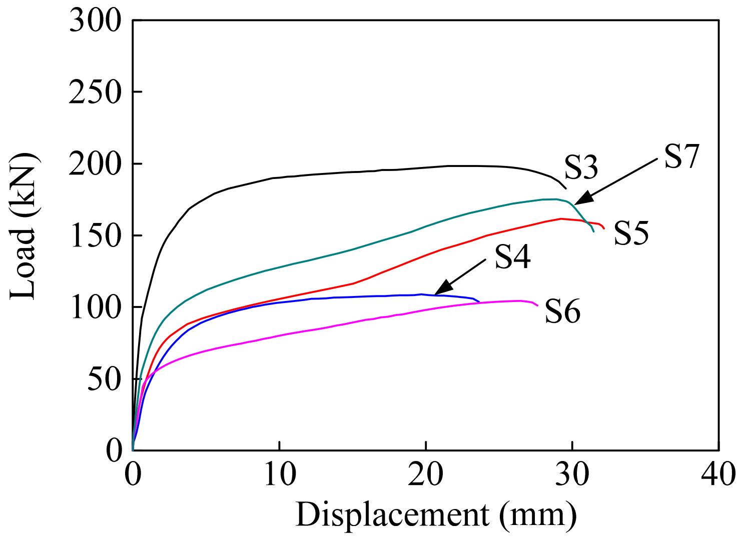
Discussion of experimental results

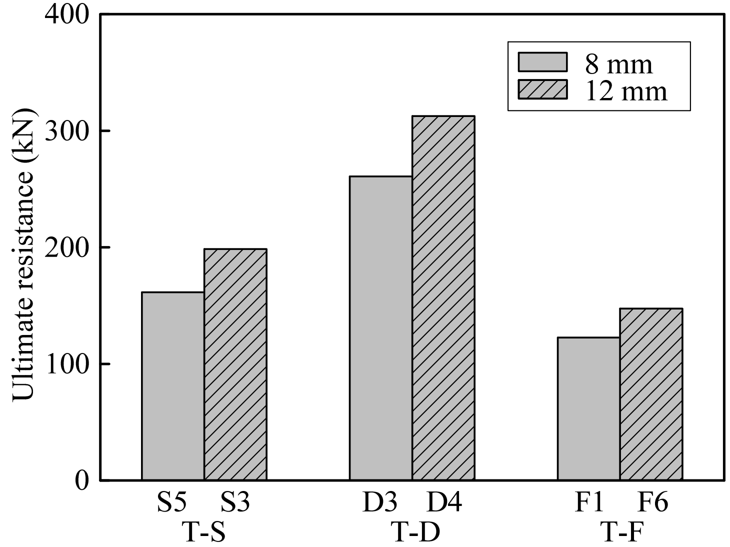
◎ Load-carrying behaviour

- **Flange thickness (S3, 12 mm vs. S5, 8mm)**

  higher ultimate resistances

  slightly lower deformation capacity



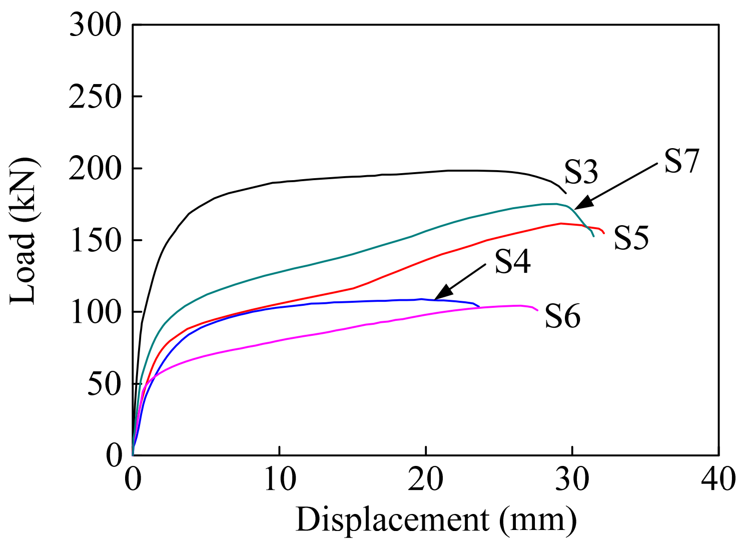


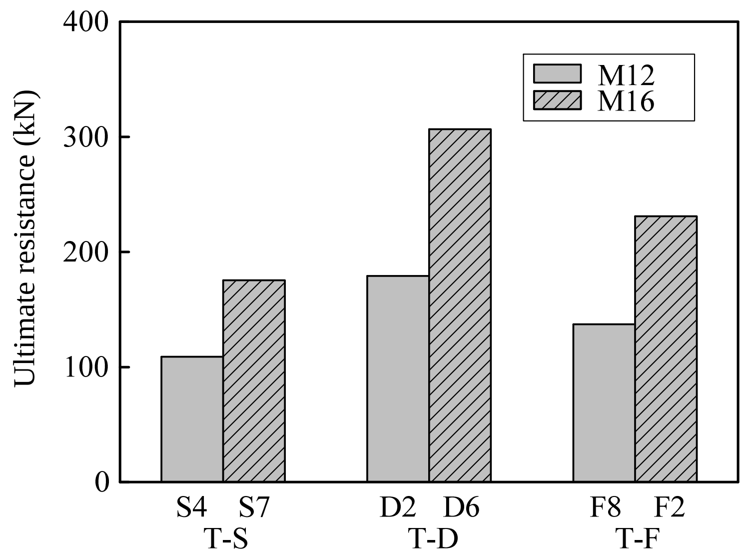
Discussion of experimental results

◎ **Load-carrying behaviour**

- **Bolt diameter (S4, 12 mm vs. S7, 16 mm)**

  higher ultimate resistances



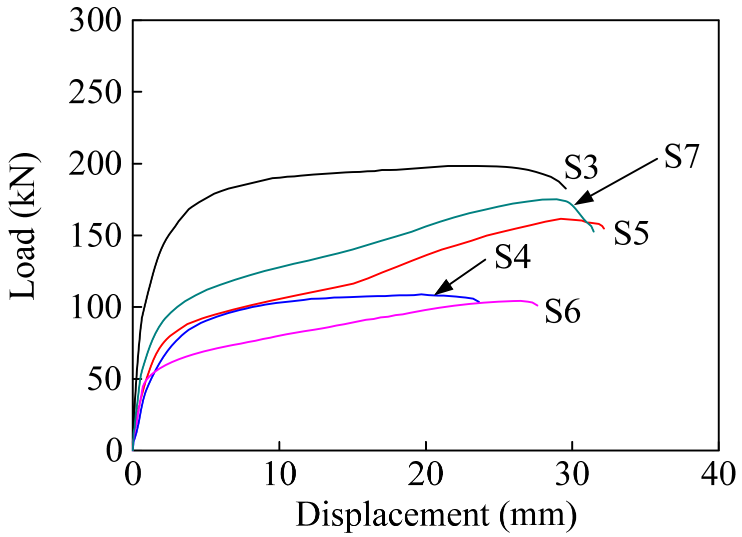


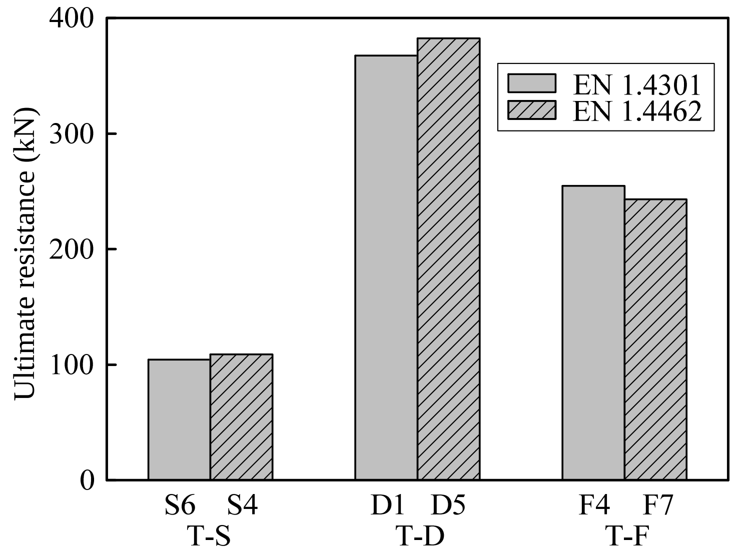
Discussion of experimental results

◎ Load-carrying behaviour

- **Flange material grade (S4, EN 1.4462 vs. S6, EN 1.4301)**

  close ultimate resistances





Discussion of experimental results

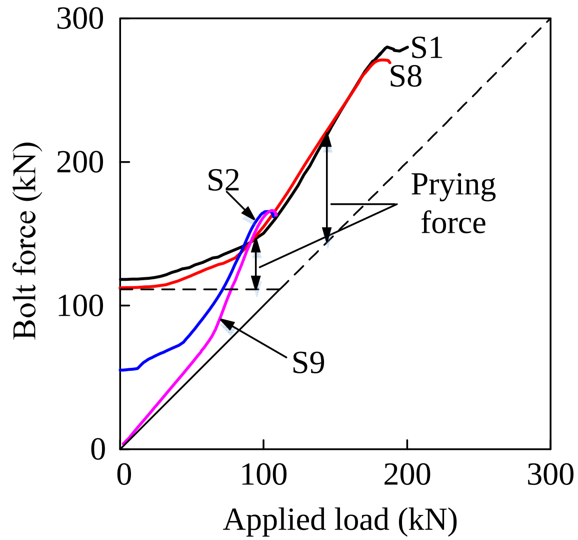
◎ Prying force

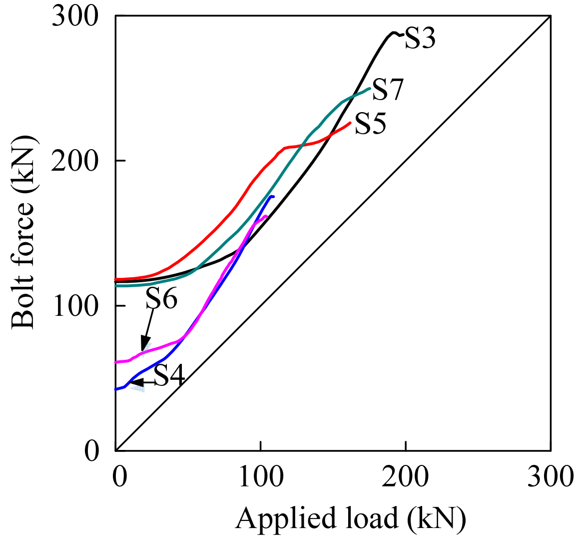
Prying force: the offset distance between the curve and the diagonal line

- Prying force gradually increased with the applied load

- The level of the bolt preloading has little effect on the amplitude of prying force at the ultimate stage
  S2 (preloaded) vs. S9 (snug tight)

- The increase of the flange thickness reduces the amplitude of the prying force
  S3 (12 mm) vs. S5 (8 mm)





Evaluation of the existing design methods

◎ Existing design methods

- **EN 1993-1-8**

$$F_{1,\ \mathrm{Rd}} = \frac{(8n-2e_{\mathrm{w}})M_{\mathrm{f,1,Rd}}}{2mn-e_{\mathrm{w}}(m+n)}$$

$$F_{2,\ \mathrm{Rd}} = \frac{2M_{\mathrm{f,2,Rd}}+n\sum F_{\mathrm{t,Rd}}}{m+n}$$

$$F_{3,\ \mathrm{Rd}} = \sum F_{\mathrm{t,Rd}}$$

- **Demonceau et al**

$$F_{2,\mathrm{Rd}} = \min\left[\frac{2M_{\mathrm{f,2,Rd}}+\frac{\sum F_{\mathrm{t,Rd}}}{2}\left(\frac{n_1^2+2n_2^2+2n_1n_2}{n_1+n_2}\right)}{m+n_1+n_2}, \frac{2M_{\mathrm{f,1,Rd}}+\frac{\sum F_{\mathrm{t,Rd}}}{2}n_1}{m+n_1}\right]$$

- **AISC manual**

$$t_{\min} = \sqrt{\frac{4Be_2}{pf_{\mathrm{u}}}}$$

$$t_{\mathrm{e}} = \sqrt{\frac{4Te_2'}{pF_{\mathrm{u}}(1+\delta\alpha')}}$$

- **JGJ 82**

$$t_{\mathrm{ec}} = \sqrt{\frac{4mN_{\mathrm{t}}^{\mathrm{b}}}{bf_{\mathrm{y}}}}$$

$$t_{\mathrm{e}} = \sqrt{\frac{4mN_{\mathrm{t}}}{\psi bf_{\mathrm{y}}}}$$

The above design formulae were presented for application in design of T-stubs made of carbon steels

Evaluation of the existing design methods

◎ Compared with the experimental results

Specimens	Experimental results $F_{u,Exp}$ (kN)	Predicted resistances from the existing design methods $F_{u,EC3}/F_{u,Exp}$	$T_{u,AISC}/F_{u,Exp}$	$N_{tu,JGJ}/F_{u,Exp}$
S1	200.2	0.53	0.87	0.40
S2	106.8	0.62	1.03	0.50
S3	198.4	0.71	0.88	0.55
S4	108.9	0.71	0.85	0.57
S5	161.6	0.39	0.45	0.29
S6	104.3	0.43	0.88	0.34
S7	175.2	0.48	0.54	0.37
S8	188.0	0.43	0.88	0.31
S9	108.9	0.60	1.01	0.49
D1	367.5	0.36	0.78	0.26
D2	179.1	0.56	0.99	0.43
D3	260.9	0.31	0.35	0.23
D4	312.5	0.61	0.77	0.45
D5	382.5	0.65	0.83	0.46
D6	306.6	0.33	0.71	0.24
D7	174.3	0.42	0.88	0.31
D8	181.6	0.55	0.98	0.42
Mean	-	**0.51**	**0.80**	**0.39**
St. dev	-	**0.13**	**0.19**	**0.11**

Generally conservative strength predictions

The AISC manual are much closer to the experimental results, which may be attributed to the introduction of material tensile strength instead of yield strength

Evaluation of the existing design methods

◎ Compared with the experimental results

Specimens	Experimental results	Predicted resistances from Demonceau et al.	
	$F_{u,Exp}$ (kN)	$F_{u,D}$ (kN)	$F_{u,D}/F_{u,Exp}$
F1	122.5	31.5	0.26
F2	230.9	54.8	0.24
F3	180.5	82.2	0.46
F4	254.8	126.7	0.50
F5	118.4	43.1	0.36
F6	147.5	67.5	0.46
F7	243.2	73.1	0.30
F8	137.1	53.9	0.39
F9	130.2	57.5	0.44
F10	172.7	82.2	0.48
Mean	-	-	**0.39**
St. dev	-	-	**0.09**

Underestimated strength predictions for the T-stubs with four bots per row

$F_{u,D}/V_{u,Exp} = 0.39$； St. dev=0.09

Conclusions

A comprehensive experimental study on structural behaviour of stainless steel bolted T-stub connections has been presented:

- The material properties of stainless steel plates and bolts were determined by separate tensile coupon tests.
- The three typical failure modes of T-stub connections were achieved, and the resulted prying forces were also examined.
- The introduction of bolt preload has little effect on the failure mode, ultimate resistance and deformation capacity, but generates significantly increased initial stiffness for the T-stub connections.
- The failure modes and tension resistances were affected by the other factors that contributed to the flexural strength of the flange and the tensile strength of the bolt.

Conclusions

A comprehensive experimental study on structural behaviour of stainless steel bolted T-stub connections has been presented:

- The existing design methods provide generally conservative predictions for the tested stainless steel bolted T-stub specimens.

- **It should be noted that the predicted strength from the existing design methods were compared with the ultimate strengths, at which the deformations clearly exceeded the serviceability limits. Hence more rational assessment would be required and is currently under way.**

Ongoing research work

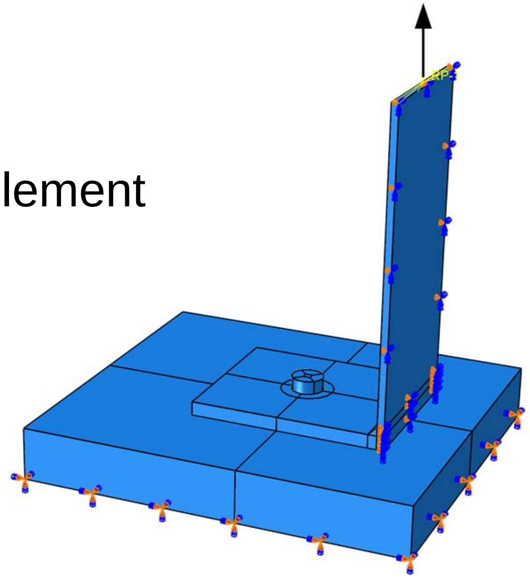
◎ Numerical studies

- ABAQUS software package, 1/2 model, C3D8R element
- Two-stage Ramberg-Osgood model
- True stress and true plastic strain

$$\sigma_{\text{true}} = \sigma_{\text{nom}}(1+\varepsilon_{\text{nom}})$$

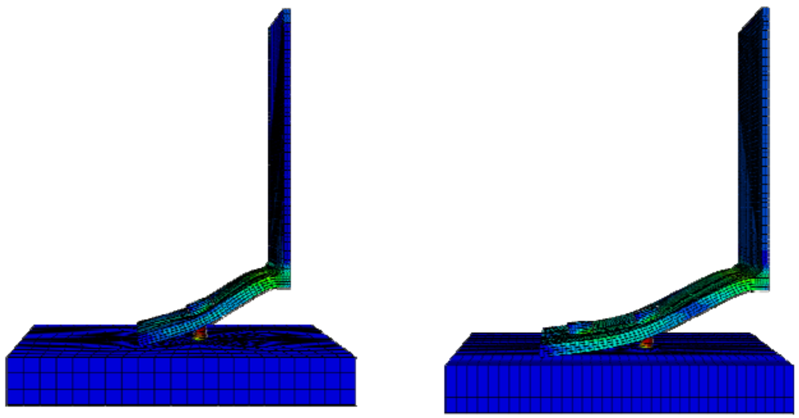
$$\varepsilon_{\text{true}}^{\text{pl}} = \ln(1+\varepsilon_{\text{nom}}) - \frac{\sigma_{\text{true}}}{E}$$

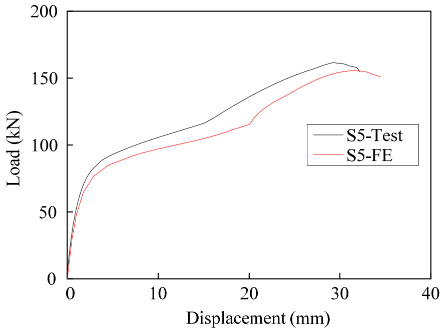
- Contact: surface to surface
- Preloading force: bolt load
- Boundary conditions: XSYMM, ENCASTRE

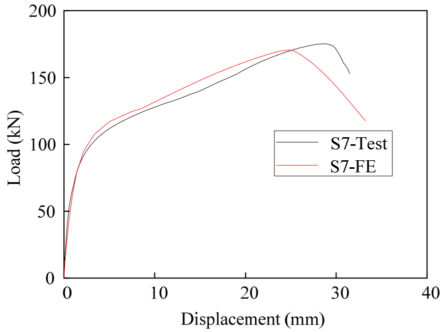


Ongoing research work

◎ Numerical studies







- **The numerical models can be directly validated against the obtained test results.**
- **Influences of the key parameters, such as material properties, flange width, geometrical dimensions, will be examined.**
- **Design proposal with improved accuracy and deign efficiency for stainless steel bolted T-stub connections will also be presented.**

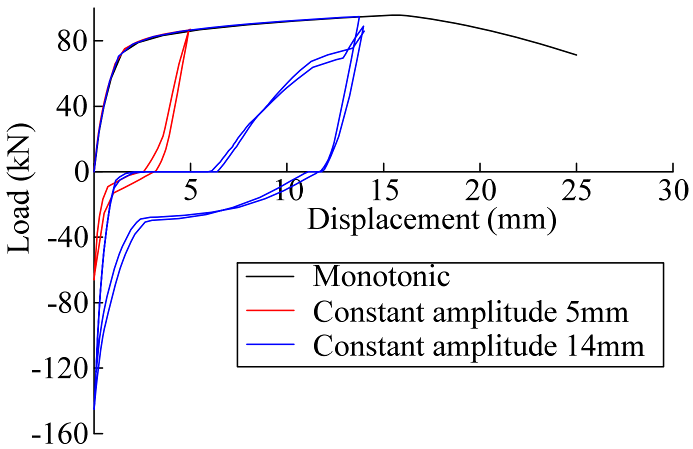
Ongoing research work

◎ Cyclic response of stainless steel bolted T-stubs

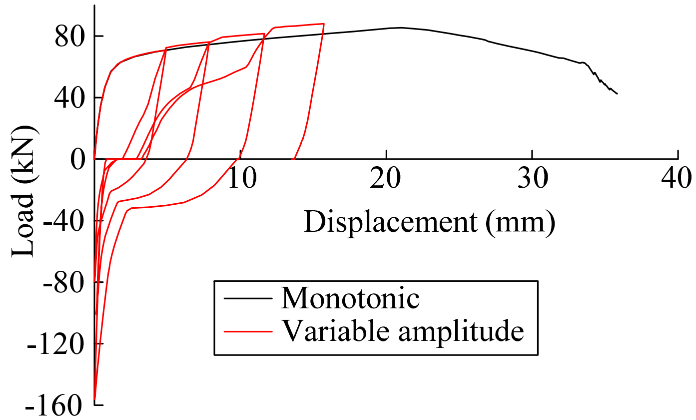
- A total of sixty test specimens of two stainless steel alloys (austenitic EN 1.4301 and duplex EN 1.4462) have been prepared.

- Three constant amplitudes and two variable amplitudes will be included in each series of the cyclic loading tests.

- Evaluation of the deformation and energy dissipation capacity of the stainless steel bolted T-stub connections will be conducted.



Constant amplitude



Variable amplitude

Acknowledgements

- The financial support from the National Natural Science Foundation of China (Grant nos. 51508424), the China Postdoctoral Science Foundation (Grant nos. 2015T80832), the Fundamental Research Funds for the Central Universities (Grant nos.2042017gf0047, 2042016kf1125) are gratefully acknowledged.

- Special thanks should be given to Jiangsu Dongge Stainless Steel Ware Co., Ltd. for fabricating the test specimens.

- Sincere thanks should also be extended to the technical staff in the Key Laboratory of Geotechnical and Structural Engineering Safety of Hubei Province, Wuhan University, for their technical support on the experimental work.

Many Thanks !