CERTIFICATE of APPRECIATION

THIS ACKNOWLEDGES THAT

Andy Prabowo, Ph.D.

Has been invited as **A GUEST SPEAKER** in the event of:

Academic License Webinar: SIMULIA Abaqus & CST Studio Suite

December 13th, 2023

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Numerical Model of Perforated Stainless Steel Beam under Four-Point Bending

Webinar Abaqus December 13th, 2023

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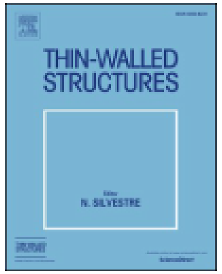
Application of Abaqus in UNTAR's Civil Engg Dept

- Abaqus has been procured at the End of 2022 through Worley Indonesia
- Current version: Abaqus 2023 (1 perpetual license)
- Application for research area:
  - ✓ Finite element model of cold-formed steel member behaviour: column, beam, shear, web crippling, and others
  - ✓ Considered at ambient and elevated temperatures
  - ✓ Future plan: direct analysis method, connection, earthquake engg

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws



Full length article

Cold-formed stainless steel beams with single web hole at elevated temperatures

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A R T I C L E I N F O

Keywords:
Cold-formed stainless steel
Direct strength method
Elevated temperatures
Perforated beams

A B S T R A C T

Steel structures are often used in buildings due to their advantage in weight-to-strength ratio. However, their structural capacity deteriorates in fire as the temperature of the structures rises. Investigation of cold-formed stainless steel (CFSS) structures at elevated temperatures is still limited, especially for rectangular hollow section (RHS) beams having a single web hole in the mid-span (perforated web). Therefore, a numerical investigation was conducted to evaluate the current design provisions to calculate the strength of such beams at

	Source title ↓	Documents 2019-22 ↓	% Cited ↓	SNIP ↓	SJR ↓	Publisher ↓
1	Thin-Walled Structures	2,714	83	1.974	1.434	Elsevier

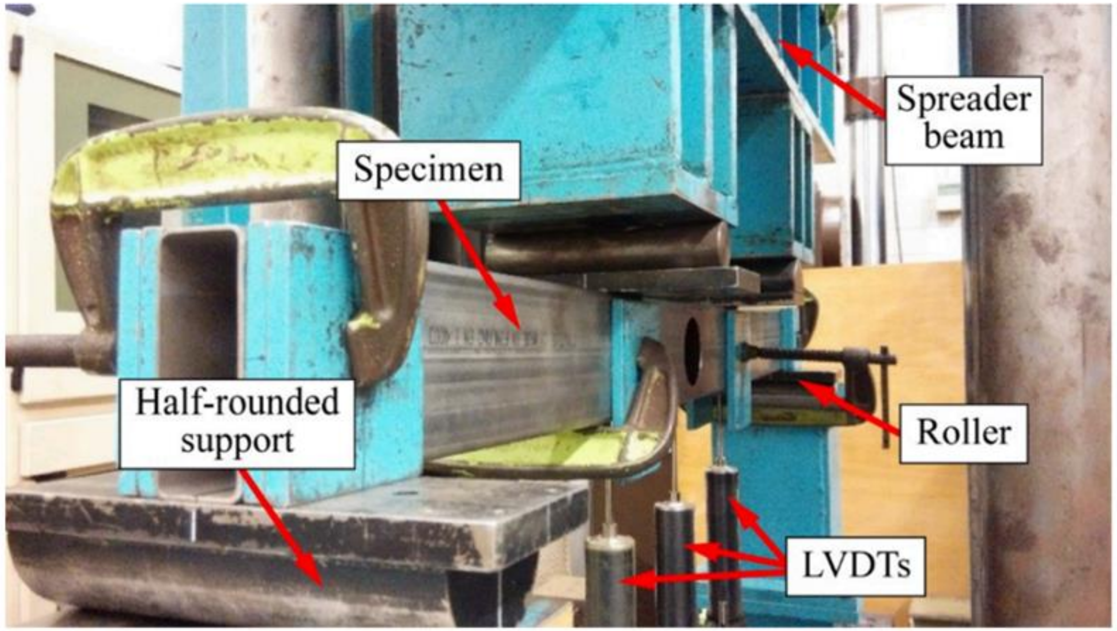


Fig. 1. Test setup of perforated RHS beam (Chen et al., 2022)

The Problem

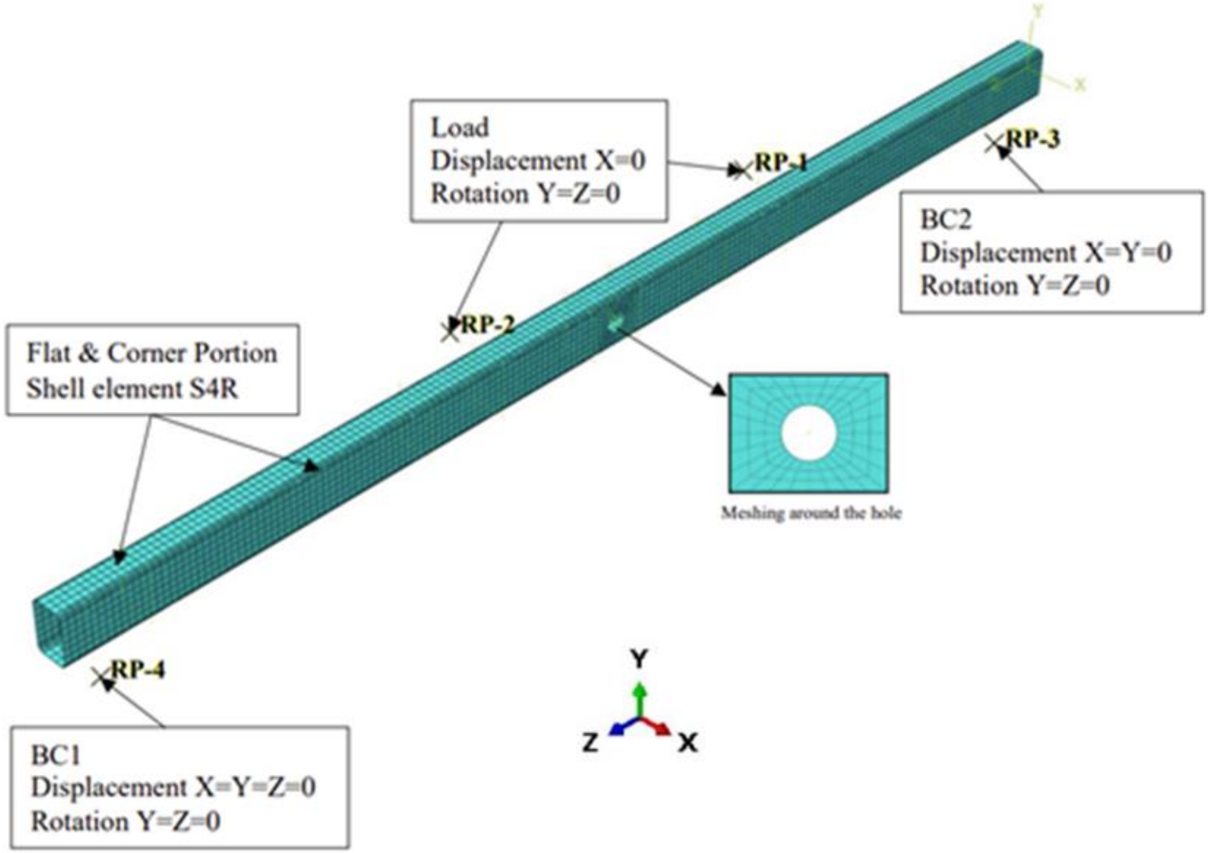


Fig. 2. Finite element model of perforated RHS beam (Prabowo et al., 2023)

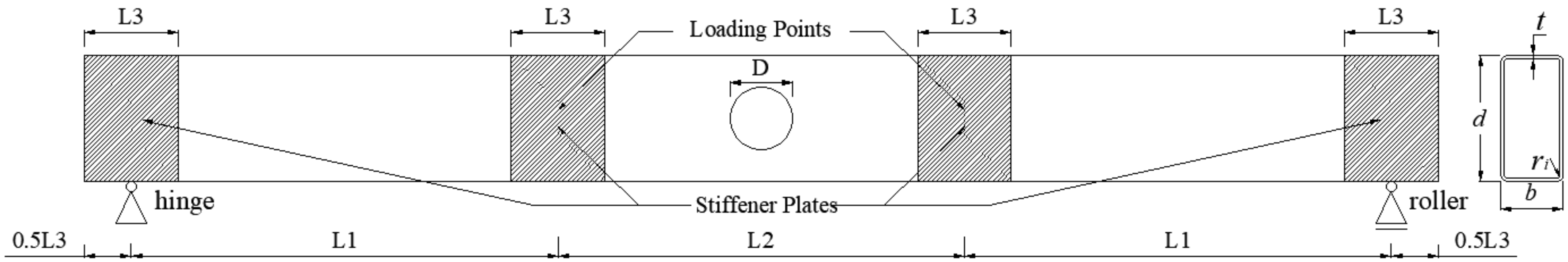
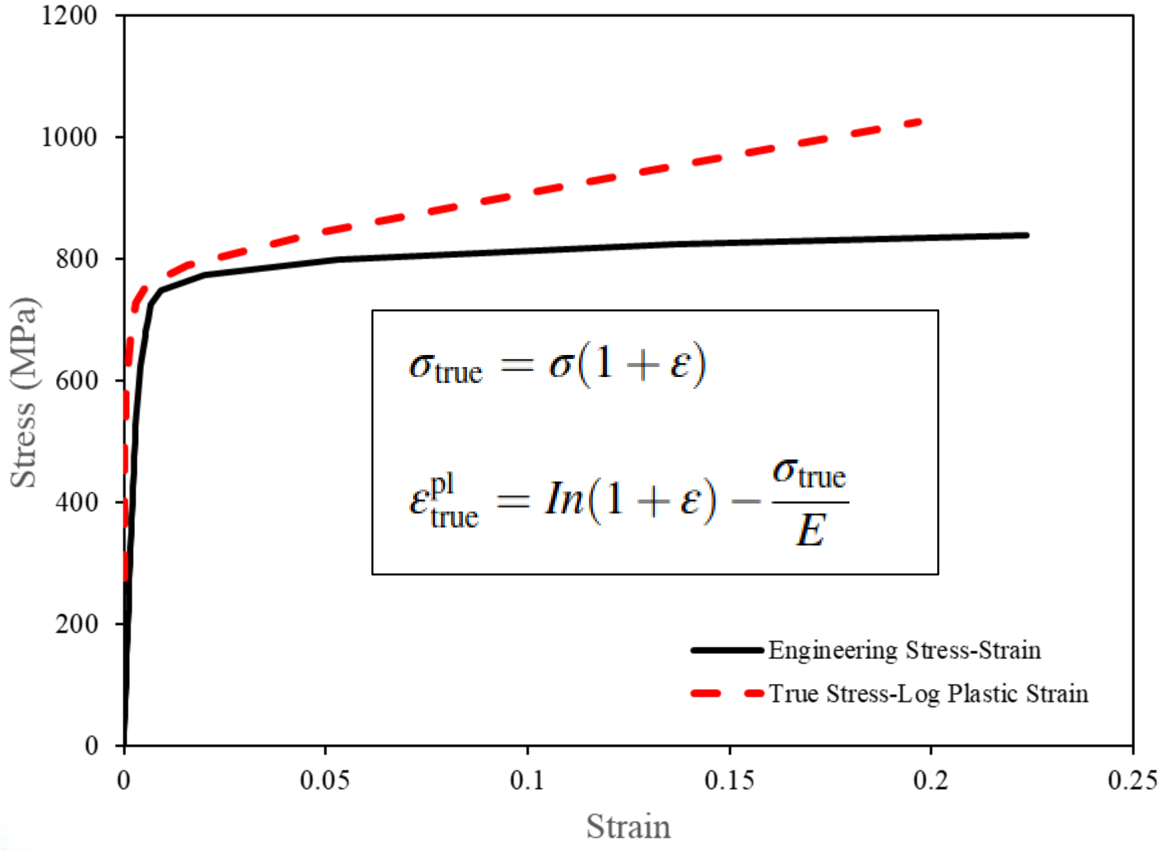


Fig. 3. Dimension of specimens

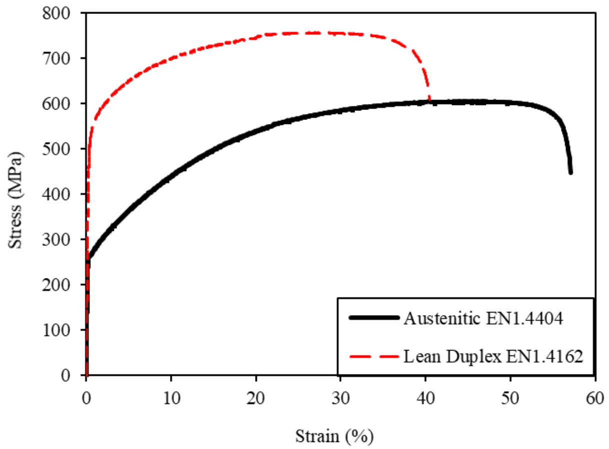
Specimen	L (mm)	H (mm)	B (mm)	t (mm)	r_o (mm)	r_i (mm)	D (%)
60×40×4-D0	1301.0	60.07	40.24	3.87	7.63	4.44	0.00
60×40×4-D20	1290.0	60.08	40.44	3.96	7.63	4.44	20.30
60×40×4-D50	1300.5	59.88	40.21	3.90	7.63	4.44	50.78
60×40×4-D80	1301.0	60.05	40.17	3.79	7.63	4.44	80.12
80×60×4-D0	1301.5	80.35	60.31	3.74	8.38	4.94	0.00
80×60×4-D20	1299.0	80.51	60.15	3.79	8.38	4.94	19.54
80×60×4-D50	1299.6	80.32	60.13	3.77	8.38	4.94	49.58
80×60×4-D50[#]	1299.0	80.33	60.33	3.93	8.38	4.94	49.19
80×60×4-D80	1298.5	80.36	60.14	3.82	8.38	4.94	78.88

Material Nonlinearity



$$\sigma_{\text{true}} = \sigma(1+\varepsilon)$$

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



Boundary conditions

- BCs were set based on DOF activation
- Replicating BCs from the experiment setup is an important setting (modelled through loading setup)
- FEA using Displacement control method → target displacements were keyed

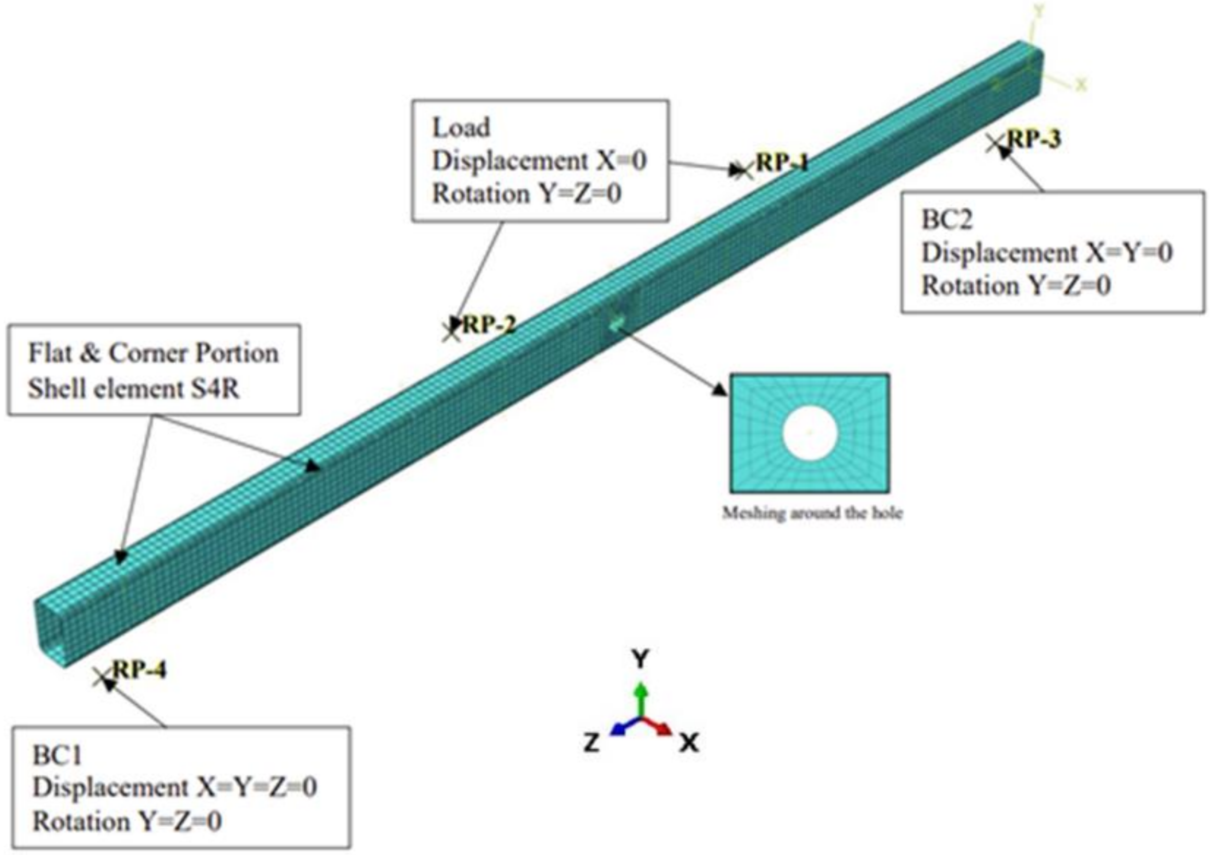
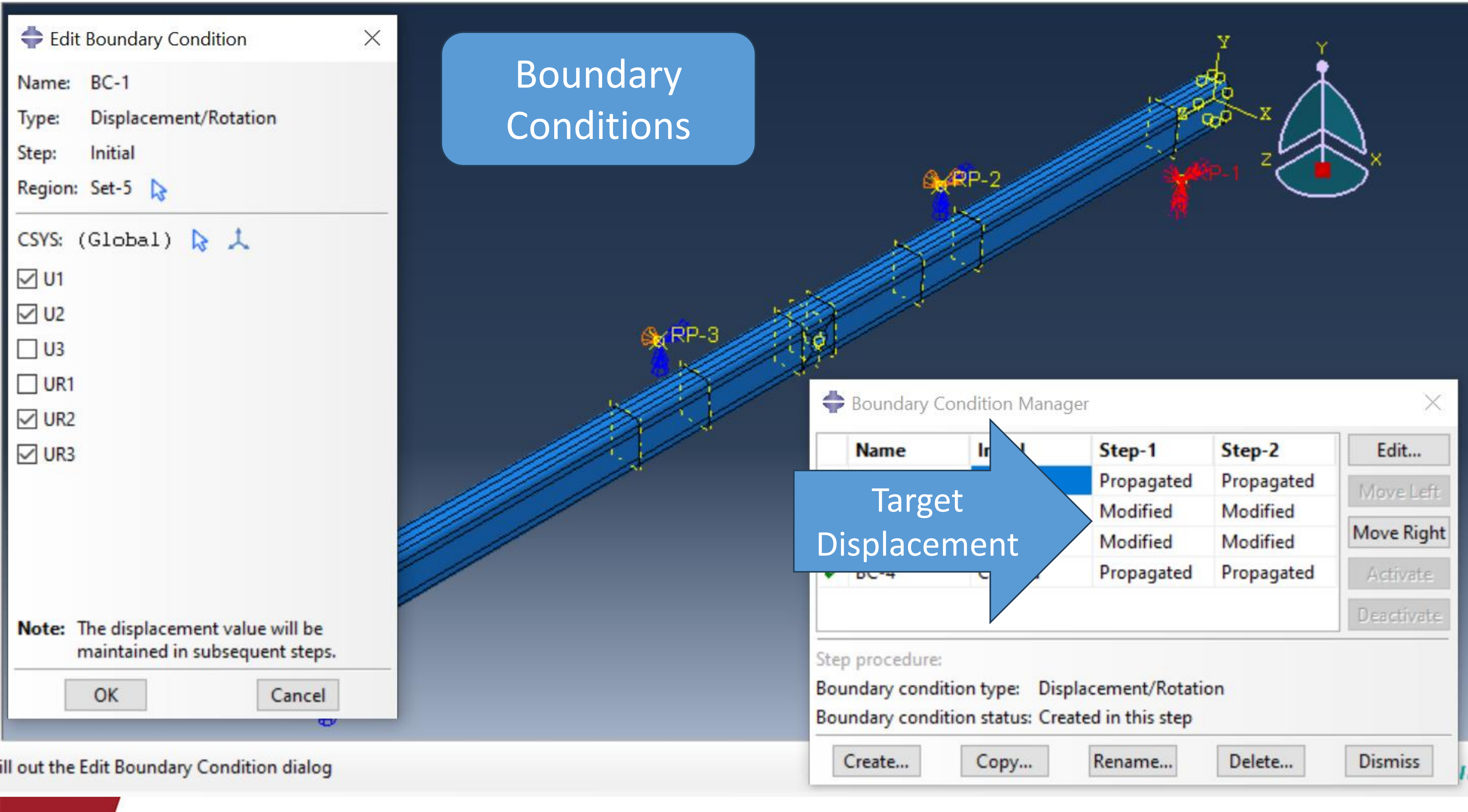
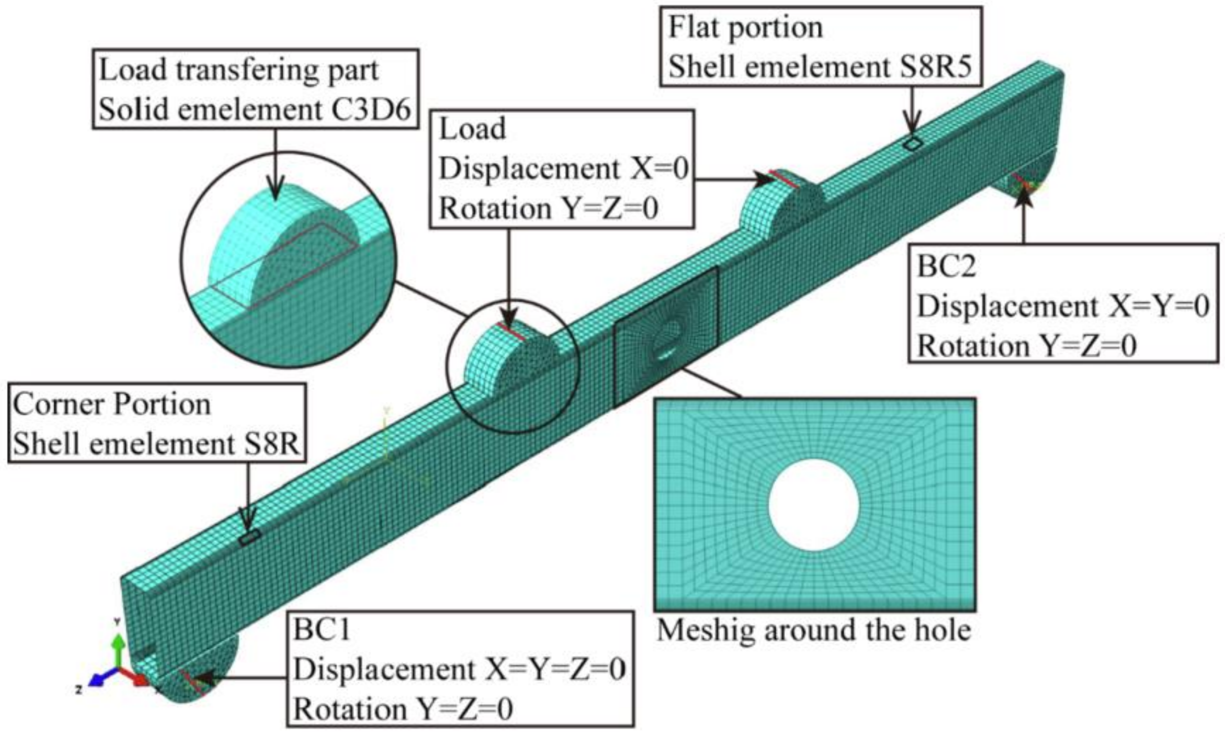


Fig. 2. Finite element model of perforated RHS beam (Prabowo et al., 2023)

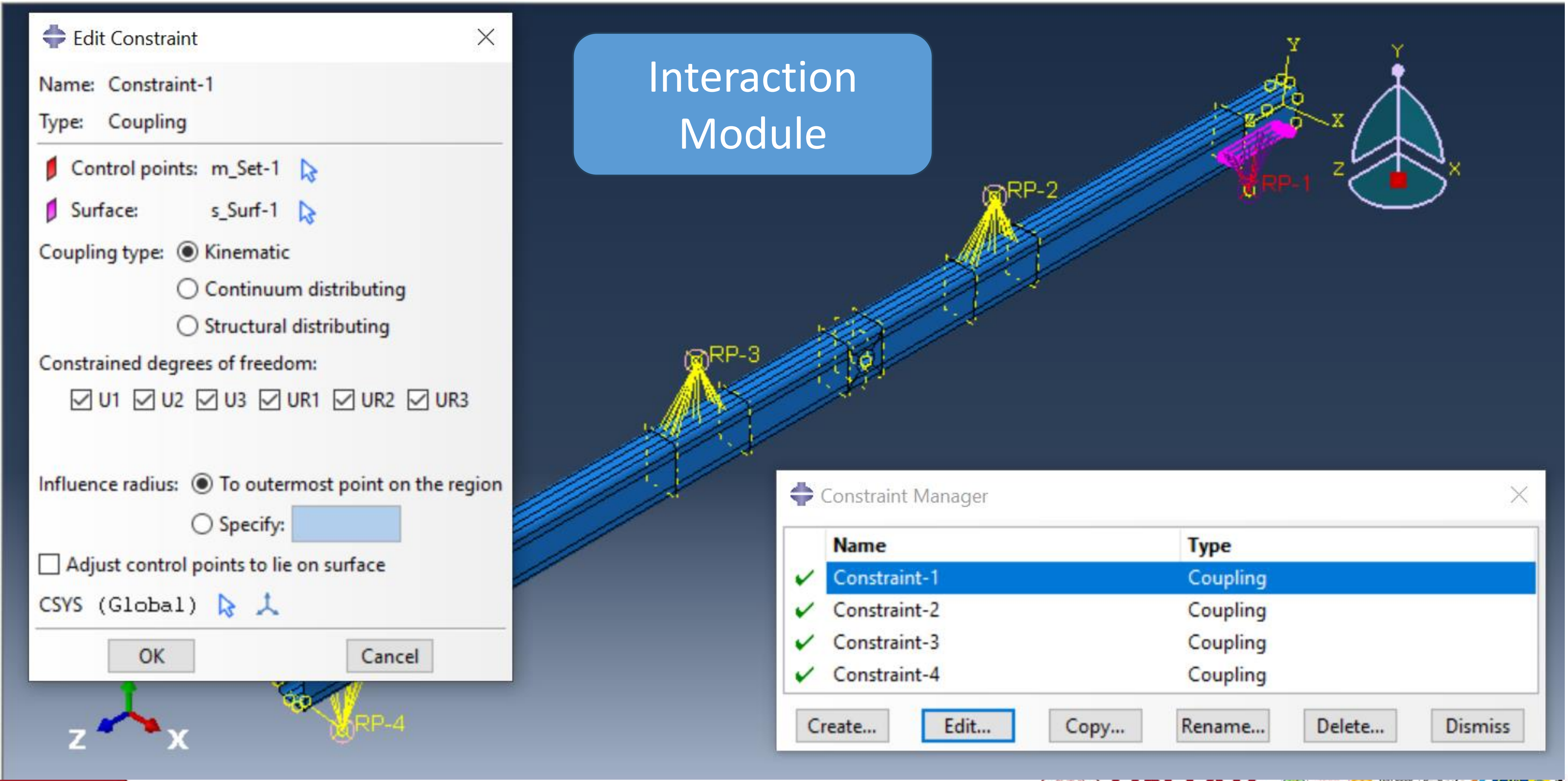

Boundary Conditions
Edit Boundary Condition
Name: BC-1
Type: Displacement/Rotation
Step: Initial
Region: Set-5
CSYS: (Global)
U1
U2
U3
UR1
UR2
UR3
Note: The displacement value will be maintained in subsequent steps.
OK
Cancel
RP-1
RP-2
RP-3
Boundary Condition Manager
Name
Step-1
Step-2
Propagated
Propagated
Modified
Modified
Modified
Modified
Propagated
Propagated
Target Displacement
Edit...
Move Left
Move Right
Activate
Deactivate
Step procedure:
Boundary condition type: Displacement/Rotation
Boundary condition status: Created in this step
Create...
Copy...
Rename...
Delete...
Dismiss
ill out the Edit Boundary Condition dialog

Finite Element Meshes

- Cold-formed steel member → shell element
- Element type: S4R, S8R, S8R5
- Loading block → solid element
- Interaction between elements should be modelled carefully



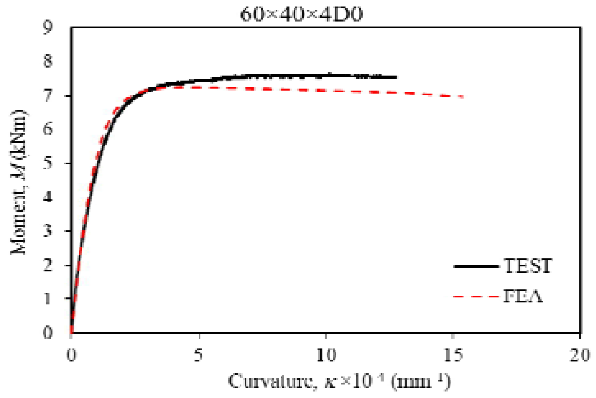
Interaction Module

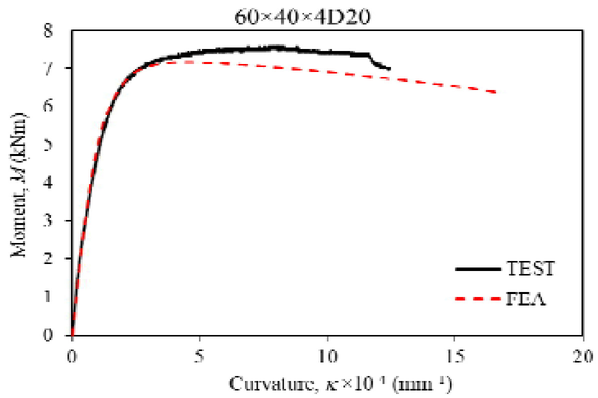


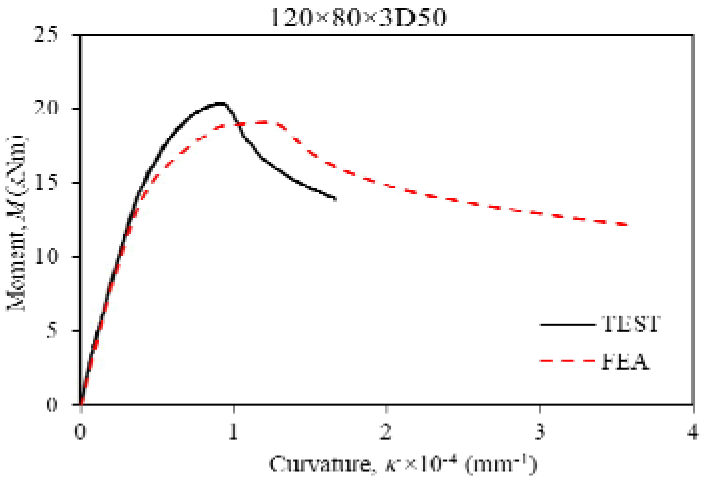
FEM Validations – Comparison of ultimate strengths

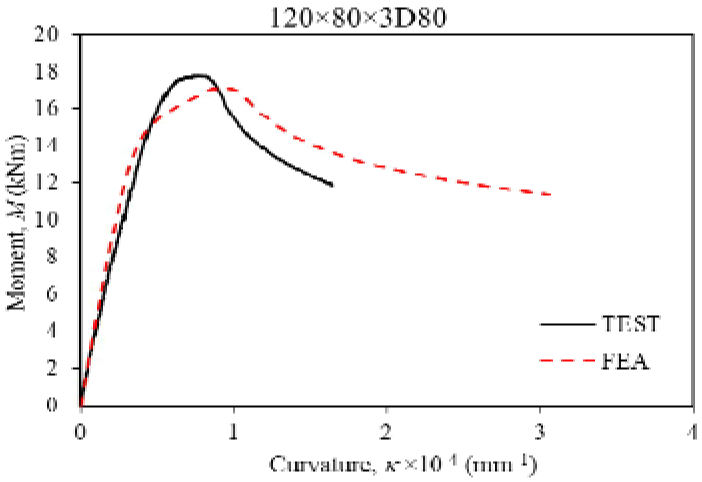
Specimen ($d \times b \times t$)	D/h (%)	M_{Test} (kNm)	M_{FEA} (kNm)	M_{Test}/M_{FEA}	K_{Test} ($.10^{-4}$)	K_{FEA} ($.10^{-4}$)	K_{Test}/K_{FEA}
60×40×4	0	7.59	7.41	1.02	4.92	5.13	0.96
	20	7.54	7.40	1.02	4.89	5.12	0.95
	50	7.12	6.76	1.05	2.11	3.00	0.70
	80	6.23	6.21	1.00	1.52	1.67	0.91
80×60×4	0	14.49	13.90	1.04	3.23	3.10	1.04
	20	14.43	13.73	1.05	3.18	3.10	1.03
	50	13.67	13.38	1.02	1.32	1.58	0.83
	50 (r)	13.88	13.38	1.04	1.41	1.58	0.89
	80	12.28	11.95	1.03	0.96	1.12	0.85
100×40×2	0	8.32	7.83	1.06	1.22	2.35	0.52
	20	8.2	7.88	1.04	1.28	1.82	0.71
	50	7.40	7.22	1.02	0.82	0.94	0.87
	50 (r)	7.57	7.22	1.05	0.84	0.94	0.89
	80	6.15	5.83	1.05	0.66	0.66	1.00
120×80×3	0	21.63	20.16	1.07	0.81	1.21	0.67
	20	21.83	20.14	1.08	0.80	1.21	0.66
	50	20.26	19.05	1.06	0.54	1.13	0.48
	80	17[illegible]5	16.04	1.11	0.47	0.47	0.98
			Mean	1.05			0.83
			COV	0.019			0.204

FEM Validations – Comparison of Moment vs Curvature Curves

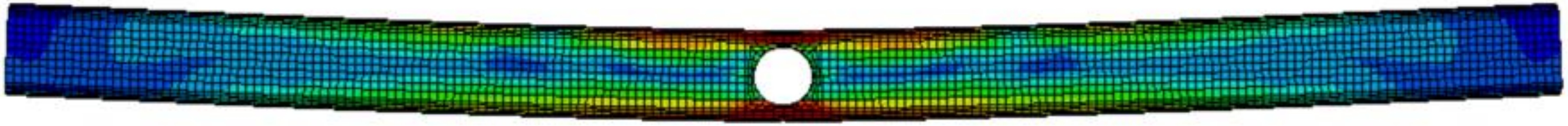








FEM Validations – Failure modes



From the three comparisons, it was concluded that the FE model developed in Abaqus could predict the test results well

Parametric study conducted reported in the journal

Parameter variations in the parametric study.

Parameters	Austenitic & Lean duplex
Sections ($d \times b \times t$)	60×40×4, 120×80×3, 300×120×4.5, 380×286×2, 380×152×1.5, 380×380×4, 380×570×4, 380×570×2
Web slenderness (h/t)	10.8 – 246.7
Inner radius to thickness ratio (r_i/t)	0.9 – 2.3
Hole diameter to web depth ratio (D/h)	0, 20%, 50%, 70%, 90%
Elevated temperatures (°C)	22, 320, 550, 660, 870 (Austenitic) 24, 300, 500, 700, 900 (Lean duplex)

Parametric Study

Flexural strength values (kNm) obtained from FEA.

Cross-section			T (°C)	Austenitic (EN 1.4301)					T (°C)	Lean duplex (EN 1.4162)				
d (mm)	b (mm)	t (mm)		D0	D20	D50	D70	D90		D0	D20	D50	D70	D90
60.07	40.24	3.87	22	7.1	6.9	6.2	5.8	5.4	24	10.3	10.1	9.4	8.9	8.1
			320	5.8	5.6	5.0	4.6	4.3	300	8.8	8.5	7.8	7.4	6.7
			550	5.4	5.2	4.6	4.2	3.9	500	7.7	7.5	6.7	6.2	5.7
			660	4.2	4.1	3.7	3.5	3.2	700	3.1	3.1	2.9	2.7	2.5
			870	0.9	0.9	0.9	0.9	0.8	900	0.8	0.8	0.8	0.7	0.7
120.02	80.3	2.89	22	18.5	18.4	17.6	15.5	13.1	24	30.3	30.3	29.0	26.5	21.2
			320	13.3	13.3	12.9	11.4	9.3	300	23.4	23.4	23.0	21.2	14.9
			550	11.4	11.4	11.0	9.7	7.9	500	18.0	18.0	17.7	16.1	11.3
			660	10.5	10.5	10.1	9.0	7.3	700	9.0	9.1	8.9	7.8	6.3
			870	3.2	3.2	3.0	2.7	2.3	900	2.5	2.5	2.4	2.2	1.8
300	120	2	22	32.2	31.4	29.9	28.2	24.1	24	48.7	47.3	45.4	43.0	36.2
			320	26.4	26.0	24.5	23.4	19.4	300	37.9	36.8	35.4	33.5	28.3
			550	22.8	22.6	21.4	20.1	17.1	500	28.9	28.1	27.0	25.5	21.5
			660	19.3	19.1	18.2	17.1	14.5	700	16.3	16.0	15.4	14.4	12.3
			870	10.0	9.5	8.1	7.8	6.2	900	5.4	5.4	5.0	4.8	4.0
380	286	2	22	47.1	46.4	44.5	43.2	36.4	24	73.4	68.5	67.4	65.4	54.1
			320	40.1	37.3	36.0	33.6	29.2	300	57.0	53.4	52.3	50.3	42.2
			550	34.4	32.1	31.0	28.4	25.1	500	43.8	40.8	39.5	38.4	32.3
			660	28.0	27.8	26.0	25.0	21.7	700	25.3	23.7	23.0	21.7	18.7
			870	13.1	12.1	11.5	10.7	10.7	900	8.1	7.5	7.2	6.5	5.7
380	152	1.5	22	26.8	26.7	26.6	23.9	20.3	24	40.1	39.4	37.5	36.0	35.7
			320	21.8	21.1	20.4	18.7	15.9	300	31.3	30.6	29.0	28.0	24.6
			550	18.8	18.3	18.2	16.1	13.7	500	23.7	23.3	22.2	21.4	18.7
			660	15.8	15.4	14.5	13.9	11.8	700	13.4	13.3	12.7	12.0	10.3
			870	7.2	6.8	6.8	6.0	5.7	900	4.4	4.2	4.2	3.8	3.2
380	380	4	22	169.6	167.5	157.5	144.4	128.2	24	290.5	289.5	274.9	219.2	192.7
			320	135.6	131.5	123.2	112.7	111.9	300	226.1	226.1	215.6	197.5	178.2
			550	122.0	115.0	104.6	97.1	81.6	500	174.2	174.5	142.8	134.8	114.2
			660	115.3	106.0	104.4	85.3	73.2	700	110.3	109.3	104.8	86.6	84.8
			870	43.1	41.7	38.8	35.7	35.6	900	33.8	33.7	32.5	30.8	25.7
380	570	4	22	196.5	195.1	169.5	153.5	136.9	24	283.8	282.5	253.7	230.8	209.8
			320	161.3	160.3	133.2	123.8	107.0	300	220.8	221.2	197.0	184.1	164.4
			550	139.2	138.4	115.2	106.7	91.9	500	171.0	169.9	150.7	141.3	125.2
			660	118.9	107.4	100.2	91.9	79.3	700	101.1	100.4	85.3	79.7	68.9
			870	50.9	50.4	43.0	38.9	33.7	900	32.5	32.2	27.0	24.7	21.4
380	570	2	22	54.4	54.4	53.0	52.6	47.9	24	78.0	77.9	77.4	75.6	69.3
			320	44.6	44.6	43.8	42.7	38.7	300	60.8	61.4	60.4	59.1	54.4
			550	38.5	38.4	37.6	36.9	33.3	500	47.0	47.3	45.6	45.6	42.2
			660	33.1	33.0	32.7	31.8	28.8	700	27.8	28.0	27.7	26.9	24.4
			870	14.9	14.8	14.6	14.0	12.3	900	8.9	9.0	8.7	8.6	7.7

Some of key findings

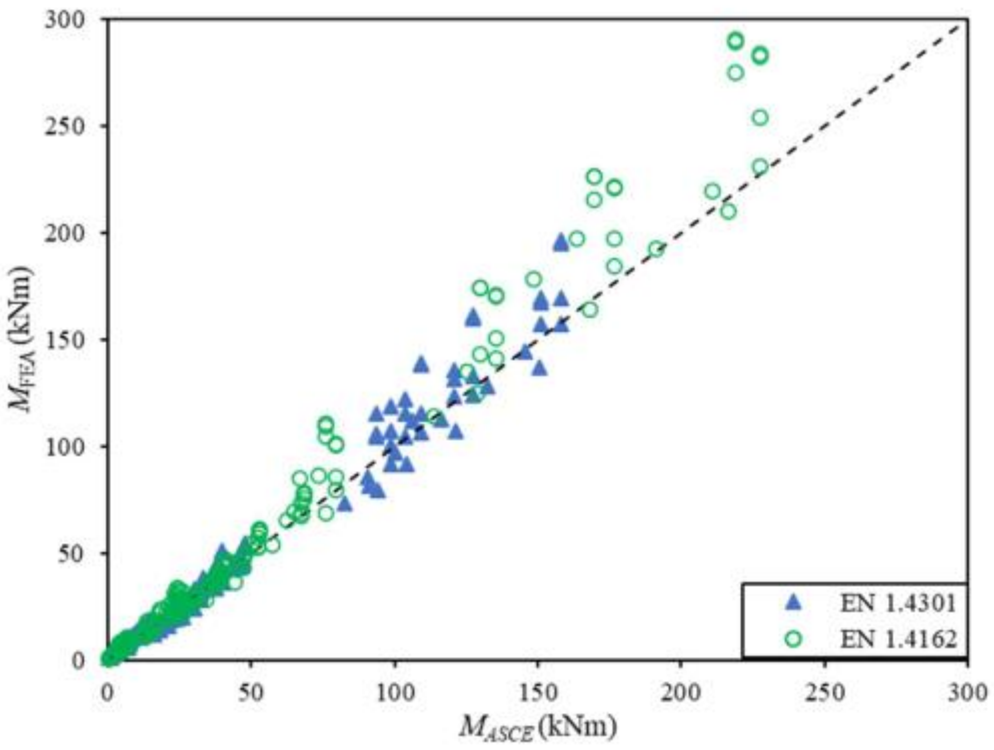


Fig. 13. Comparison of nominal flexural strengths obtained from FEA and ASCE [18] at various temperatures.

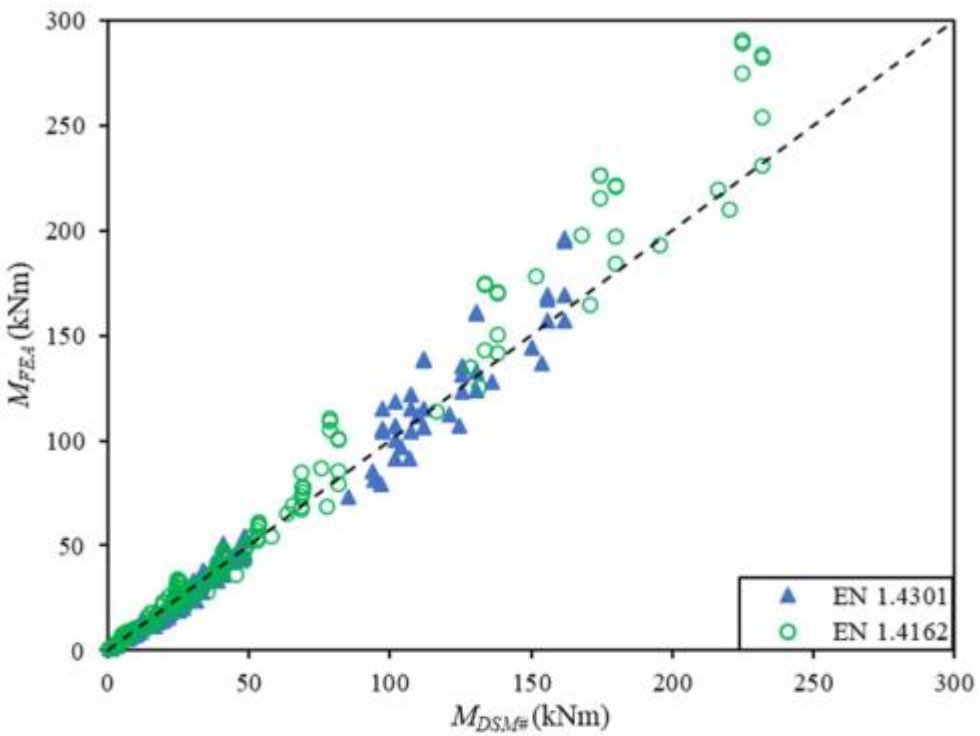


Fig. 14. Comparison of nominal flexural strengths obtained from FEA and modified DSM equations [22] at various temperatures.

Results from Reliability Analyses

Table 5

Comparison between FEA results with nominal strengths predicted from design rules for cold-formed stainless steel RHS beams without a web hole (sections with $D = 0$).

	M_{FEA}/M_{ASCE}	$M_{FEA}/M_{DSM\#}$	$M_{FEA}/M_{AS/NZS}$	M_{FEA}/M_{EC3}	$M_{FEA}/M_{EC3\#}$
Austenitic (EN 1.4301)					
Number of data	40	40	40	40	40
Mean (P_m)	1.24	1.11	1.16	1.26	1.41
COV (V_P)	0.249	0.146	0.283	0.129	0.202
Resistance factor (ϕ)	0.90	0.90	0.9	0.91	1.00
Reliability index (β_o)	2.73	3.03	2.22	3.39	2.99
% ratio < 1	15%	30%	23%	0%	8%
Smallest ratio	0.93	0.90	0.81	1.00	0.89
Kruppa criteria	Passed	Failed	Failed	Passed	Passed
Lean duplex (EN 1.4162)					
Number of data	40	40	40	40	40
Mean (P_m)	1.23	1.14	1.17	1.32	1.43
COV (V_P)	0.178	0.115	0.199	0.086	0.210
Resistance factor (ϕ)	0.90	0.90	0.9	0.91	1.00
Reliability index (β_o)	2.87	2.97	2.39	3.53	2.68
% ratio < 1	2.5%	17.5%	20%	0%	8%
Smallest ratio	0.98	0.95	0.87	1.14	0.93
Kruppa criteria	Passed	Passed	Failed	Passed	Passed

Table 6

Comparison between FEA results with nominal strengths predicted from design rules for cold-formed stainless steel RHS beams with a web hole (sections with $D > 0$).

	M_{FEA}/M_{ASCE}	$M_{FEA}/M_{DSM\#}$	$M_{FEA}/M_{AS/NZS}$	M_{FEA}/M_{EC3}	$M_{FEA}/M_{EC3\#}$
Austenitic (EN 1.4301)					
Number of data	160	160	160	160	160
Mean (P_m)	1.12	0.99	1.17	1.22	1.34
COV (V_P)	0.252	0.150	0.207	0.152	0.189
Resistance factor (ϕ)	0.90	0.90	0.90	0.91	1.00
Reliability index (β_o)	2.46	2.61	2.69	3.18	2.93
% ratio < 1	42%	59%	18%	3%	9%
Smallest ratio	0.73	0.70	0.85	0.94	0.88
Kruppa criteria	Failed	Failed	Passed	Passed	Passed
Lean duplex (EN 1.4162)					
Number of data	160	160	160	160	160
Mean (P_m)	1.13	1.03	1.19	1.26	1.36
COV (V_P)	0.195	0.136	0.154	0.120	0.213
Resistance factor (ϕ)	0.90	0.90	0.90	0.91	1.00
Reliability index (β_o)	2.50	2.48	2.72	3.16	2.52
% ratio < 1	31%	49%	13%	3%	8%
Smallest ratio	0.76	0.74	0.89	0.98	0.87
Kruppa criteria	Failed	Failed	Passed	Passed	Passed

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Prabowo, A., Huang, Y., & Young, B. (2023). Cold-formed stainless steel beams with single web hole at elevated temperatures. *Thin-walled Structures*, 111321

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