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INFLUENCE OF LOADING BLOCK BOUNDARY CONDITIONS ON THE RESISTANCE OF I-GIRDERS

Summary: During incremental bridge launching, patch loading is transferred through launching shoes. In this case, rotation of the loading block about the longitudinal axis of the girder is usually restrained. However, in some practical applications, such as crane runway girders subjected to wheel loads, the “loading block” is free to rotate. Therefore, this paper investigates the influence of loading block boundary conditions on the ultimate resistance of thin-walled I-girders. The analysis was carried out using a geometrically and materially nonlinear finite element model developed in *Abaqus*. The results show that web thickness, flange thickness and web height, as well as their interaction, have the greatest influence on the ultimate resistance. In addition, the parameter β, defined as the ratio between flange torsional stiffness and web bending stiffness, was evaluated. The results indicate that β cannot be considered a sufficient parameter for describing the influence of loading block boundary conditions.

Keywords: patch loading, boundary conditions, loading block, I-girders

UTICAJ GRANIČNIH USLOVA BLOKA ZA NANOŠENJE OPTEREĆENJA NA NOSIVOST I-NOSAČA

Rezime: Tokom montaže mostova metodom naguravanja lokalno opterećenje (*patch loading*) se prenosi preko *launching shoe* elemenata. Uobičajeno je da je spriječena rotacija bloka za nanošenje opterećenja oko podužne ose nosača. U praksi postoje slučajevi kada rotacija bloka nije spriječena -opterećenje kranske staze točkovima krana. Zbog toga je u radu analiziran uticaj graničnih uslova bloka za nanošenje opterećenja na graničnu nosivost tankozidnih I-nosača. Analiza je sprovedena primjenom geometrijski i materijalno nelinearnog numeričkog modela razvijenog u programskom paketu Abaqus. Rezultati pokazuju da najveći uticaj na graničnu nosivost imaju: debljina rebra, debljina nožice i visina rebra, odnosno njihov odnos. Dodatno je ispitan parametar β, koji predstavlja odnos torzione krutosti nožice i savojne krutosti rebra. Dobijeni rezultati pokazali su da se β ne može smatrati dovoljnim parametrom za opis uticaja graničnih uslova bloka.

Ključne reči: lokalno opterećenje, granični uslovi, blok za unošenje opterećenja, I-nosači

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1. INTRODUCTION

Patch loading induces a complex stress state in the load introduction zone. In thin-walled girders, local web buckling is the dominant failure mode, with deformations concentrated near the load application point.

Patch loading of thin-walled steel I-girders has been extensively investigated experimentally, theoretically and numerically. Previous research has focused on ultimate resistance, failure mechanisms, and the influence of geometric and material parameters; these findings form the basis of the design models in EN 1993-1-5 [1].

Lagerqvist et al. [2,3] investigated the failure mechanism and behaviour of patch-loaded girders in detail. Later studies by Granath [4], Gozzi [5], and researchers from the region [6–8] confirmed the significant influence of girder geometry, geometric imperfections and material properties on ultimate resistance.

During incremental bridge launching, patch loading is transmitted onto bridge girder through launching shoes. Granath [4], Gozzi [5], and Rogač et al. [6,8] showed that the contact conditions between the loading element and the girder flange significantly affect the stress distribution and ultimate resistance. In launching shoe systems, rotation of the loading block about the longitudinal girder axis is usually restrained, whereas this restraint is generally absent under crane wheel loads on crane runway girders. The influence of this rotational restraint on the ultimate resistance of patch-loaded I-girders has not been sufficiently investigated and is the subject of this paper.

2. NUMERICAL ANALYSIS

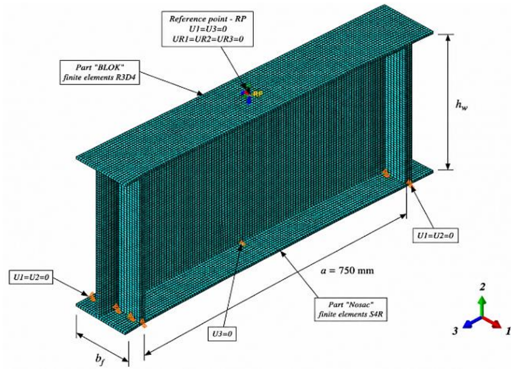
The influence of loading block boundary conditions on the ultimate resistance of patch-loaded I-girders was investigated using the finite element analysis. For the purposes of this study, geometrically and materially nonlinear numerical models were developed in the Abaqus software package [9]. The numerical analysis was carried out in two phases. In the first phase, a linear stability analysis (Eigenvalue Buckling Analysis) was performed. This analysis is based on linear elastic stability theory and was used to determine the characteristic buckling modes of the structure, which were subsequently employed in the second phase to model geometric imperfections, in accordance with the recommendations of Annex C of EN 1993-1-5 [1]. The obtained buckling mode was introduced into the geometry of the nonlinear numerical model intended for nonlinear analysis, with the imperfection amplitude scaled to a value corresponding to 80% of the functional tolerances prescribed by the standard [10].

In the second phase, a nonlinear analysis was performed using the Riks method. The Riks method enables simulation of the actual structural response under increasing load. During the analysis, the load is gradually increased while the changes in structural deformation and stiffness are monitored simultaneously. This makes it possible to identify the onset of yielding, the development of local web buckling, and the post-buckling behaviour of the structure.

2.1. NONLINEAR NUMERICAL MODEL – PHASE II

The nonlinear numerical model consists of two parts: the girder and the loading block. The girder was modelled as a deformable body using four-node quadrilateral shell elements with reduced integration (S4R), which represent a standard choice for the analysis of thin-walled steel structures. The loading block was modelled as a rigid body (*Discrete Rigid Body*), enabling straightforward definition of the boundary conditions and load application through the block reference point. Contact between the loading block and the upper flange of the girder was modelled using a surface-to-surface contact formulation. The rigid surface of the block was defined as the master surface, whereas the flange surface was defined as the slave surface; friction between the contact surfaces was neglected.

In Abaqus, nonlinear material behaviour is defined by inputting true stress and plastic strain values. Therefore, the nominal (engineering) stress and strain values were previously transformed into the corresponding true values using the given expressions [9]. Based on the resulting data, a trilinear material model was established [6], as shown in *Figure 1 (right)*. Particular attention was devoted to modelling the boundary conditions of the loading block, which constitute the subject of this study. Depending on the analysed case, rotation of the block about the longitudinal axis of the girder was either permitted or restrained. The initial configuration of the numerical model is shown in *Figure 1 (left)*, while selected geometric and material properties were varied for the purposes of the parametric analysis. For each analysed model, analyses were performed with free and restrained rotation of the loading block, and the influence of the boundary conditions was assessed by comparing the obtained ultimate resistances.



Limit points of selected steel grades, which define the bilinear plastic region.

Steel grade *S*	Limit point	σ_{nom} [MPa]	ε_{nom}	σ_{true} [MPa]	ε_{true}	$\varepsilon_{true,pl}$
*S*235	Yield	235		235		0.00000
	Hardening	235	0.01	237.35	0.00995	0.00882
	Ultimate	360	0.1	396	0.09531	0.09342
Basic material model*	Yield	273		273		0.00000
	Hardening	273	0.01	275.73	0.00995	0.00864
	Ultimate	380	0.1	418	0.09531	0.09332
*S*355	Yield	355		355		0.00000
	Hardening	355	0.01	358.55	0.00995	0.00824
	Ultimate	490	0.1	539	0.09531	0.09274
*S*450	Yield	440		440		0.00000
	Hardening	440	0.01	444.4	0.00995	0.00783
	Ultimate	550	0.1	605	0.09531	0.09243

* Corresponds to *S*275

Figure 1: Boundary Conditions of the Nonlinear Numerical Model (Left) and Material Characteristics of All Steel Grades Considered in the Parametric Analysis (Right)

The developed failure mechanism was also analysed for all models. In all cases, the characteristic failure mode associated with patch loading was confirmed (*Figure 2*), characterised by local web buckling and the development of a plastic zone directly beneath the load application area.

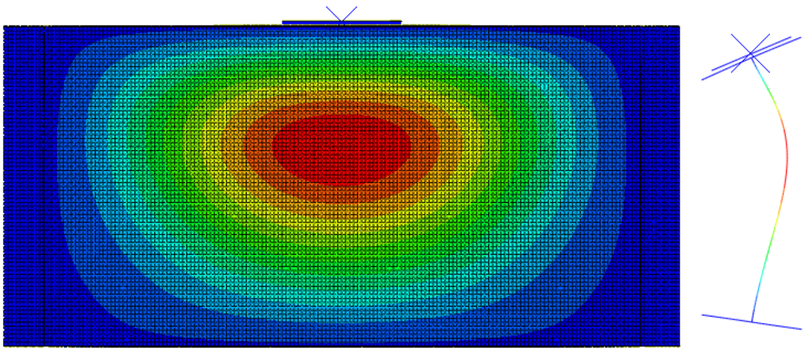


Figure 2: Characteristic Failure Mode for Patch Loading

2.2. PARAMETRIC ANALYSIS

To investigate the influence of loading block boundary conditions on the ultimate resistance of patch-loaded I-girders, a parametric analysis was performed using the previously described numerical models. The analysis was based on the systematic variation of individual geometric and material parameters, while all other parameters were kept constant. This enabled an assessment of the individual influence of each analysed parameter on the variation in ultimate resistance. For each analysed model, the ultimate resistance was determined for free ($F_{UR3\neq0}$) and limited ($F_{UR3=0}$) rotation of the loading block. To quantify the influence of the loading block boundary conditions, the factor k was defined as the relative change in ultimate resistance resulting from restrained block rotation. The factor k was determined using *Eq. (1)*:

$$k = \frac{F_{UR3=0} - F_{UR3\neq0}}{F_{UR3=0}} * 100\ (\%) \quad (1)$$

The parametric analysis included variations in web thickness (t_w), flange thickness (t_f), steel grade (S), web depth (h_w), flange width (b_f) and load application length (s_s).

2.2.1. Influence of Web Thickness t_w on Factor k

The significance of web thickness on the ultimate resistance of patch-loaded I-girders was confirmed in the study by Chacón et al. [11]. The web thickness was varied from 2 mm to 6 mm in increments of 1 mm, while two characteristic flange thicknesses were considered: $t_f = 6$ mm and $t_f = 18$ mm. The analysis was carried out on an I-girder with a spacing between transverse stiffeners of $a = 750$ mm, a web depth of $h_w = 400$ mm, a flange width of $b_f = 150$ mm, and steel grade S275. The ultimate resistance values of the models are provided in the *Appendix*, while the change in ultimate resistance resulting from restrained rotation of the loading block is shown in *Figure 3.*

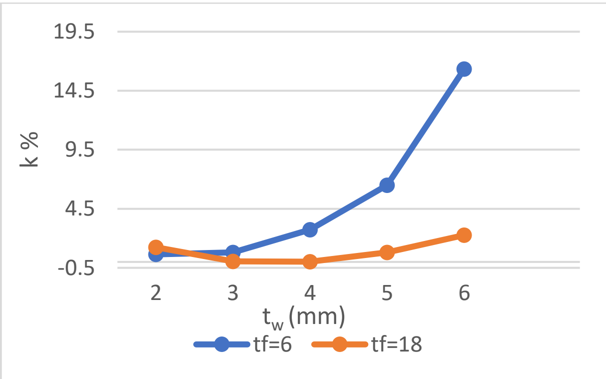


Figure 3: Influence of t_w on k

It can be observed from the diagram that the influence of web thickness on factor k depends on the flange thickness. For girders with a flange thickness of $t_f = 6$ mm, factor k increases with increasing web thickness. For lower web thickness values ($t_w = 2$–3 mm), the difference is almost negligible, whereas for $t_w \geq 4$ mm it becomes more pronounced, reaching 16.34% for $t_w = 6$ mm. In contrast, for girders with a flange thickness of $t_f = 18$ mm, the change in ultimate resistance remains small throughout the analysed range. The obtained results indicate that the greatest difference occurs when the ratio of t_w to t_f approaches 1, suggesting that web thickness cannot be considered as an appropriate governing parameter, but rather as part of an influential parameter.

2.2.2. Influence of Flange Thickness t_f on Factor k

The flange thickness was varied from 6 mm to 18 mm in increments of 2 mm, while two characteristic web thicknesses were considered: $t_w = 2$mm and $t_w = 6$ mm. The analysis was carried out on an I-girder with a spacing between transverse stiffeners of $a = 750$ mm, a web depth of $h_w = 400$ mm, a flange width of $b_f = 150$ mm, and steel grade S275. The ultimate resistance values are provided in the *Appendix*, while the influence of flange thickness on factor k is shown in *Figure 4*.

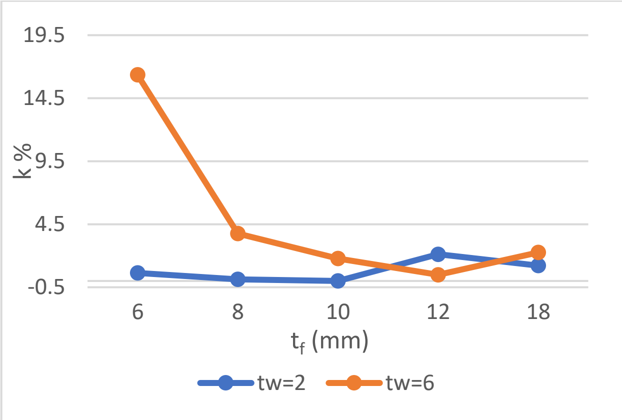


Figure 4: Influence of t_f on k

It can be observed that the influence of flange thickness on factor k depends on the web thickness. For girders with a web thickness of t_w = 2 mm, factor k remains low throughout the analysed range of flange thicknesses and shows no pronounced trend. In contrast, for girders with a web thickness of t_w = 6 mm, a significant decrease in factor k is observed with increasing flange thickness. The largest difference, 16.34%, was obtained for t_f = 6 mm, after which the values decrease sharply. The results indicate that increasing the flange thickness significantly reduces the effect of restrained block rotation in girders with a thicker web, whereas this effect is negligible in girders with a thin web. The above indicates that flange thickness cannot be considered as an appropriate governing parameter, but rather as part of an influential parameter.

2.2.3. Influence of Steel Grade on Factor *k*

Steel grades ranging from S235 to S440 were analysed for two characteristic flange thicknesses (t_f = 6 mm and t_f = 18 mm), as well as for two characteristic web thicknesses (t_w = 2 mm and t_w = 6 mm). The analysis was carried out on an I-girder with a spacing between transverse stiffeners of a = 750 mm, a web depth of h_w = 400 mm, and a flange width of b_f = 150 mm. The ultimate resistance values are presented in tabular form in the *Appendix*, while the influence of steel grade on factor k is shown in *Figure 5*, on the right and left, respectively.

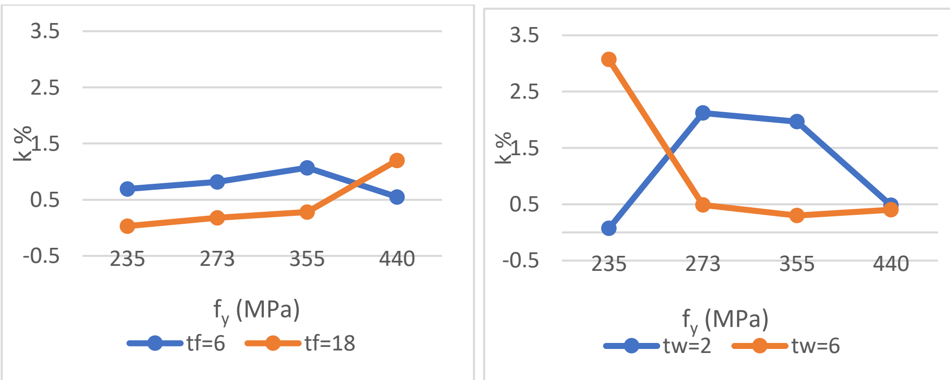


Figure 5: Influence of f_y on k

It is evident that the influence of steel grade is not unambiguous. For both analysed cases, no monotonic relationship is observed between the material yield strength and the change in ultimate resistance. The obtained results indicate that variation in steel grade alone does not have a dominant influence on the effect of restrained block rotation.

2.2.4. Influence of Web Depth h_w on Factor k

The web depth was varied from 400 mm to 1000 mm in increments of 100 mm, while two characteristic web thicknesses were considered: $t_w = 2$ mmand $t_w = 6$ mm. The analysis was carried out on an I-girder with a spacing between transverse stiffeners of $a = 750$ mm, a flange width of $b_f = 150$ mm, a flange thickness of $t_f = 12$ mm, and steel grade S275. The ultimate resistance values are provided in the *Appendix*, while the influence of web depth on factor k is shown in *Figure 6.*

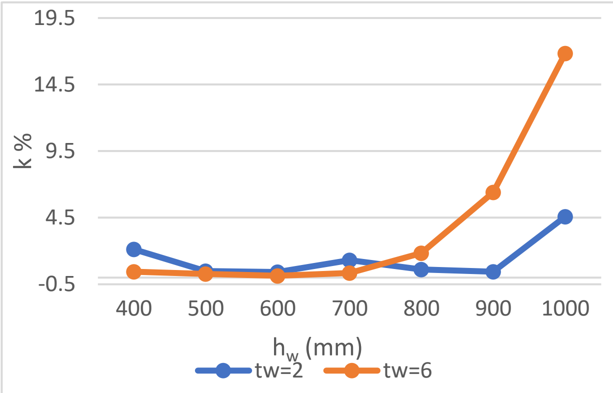


Figure 6: Influence of hw on k

It can be observed that the influence of web depth depends on the web thickness. For girders with a web thickness of $t_w = 2$ mm, the difference in ultimate resistance remains small over almost the entire analysed range of web depths, with only a slight increase at the largest analysed web depth ($h_w = 1000$ mm). In contrast, for girders with a web thickness of $t_w = 6$ mm, the difference is negligible for web depths up to 700 mm, after which it increases sharply. The most pronounced effect of restrained block rotation was obtained for the largest analysed web depth, where the difference in ultimate resistance reaches 16.85%. The results indicate that increasing web depth significantly increases the effect of restrained block rotation in girders with a thicker web, whereas this effect is considerably less pronounced in girders with a thin web.

2.2.5. Influence of Load Application Length s_s on Factor k

The load application length was varied from 50 mm to 250 mm in increments of 50 mm, while two characteristic web thicknesses were considered: $t_w = 2$ mm and $t_w = 6$ mm. The analysis was carried out on an I-girder with a spacing between transverse stiffeners of $a = 750$ mm, a web depth of $h_w = 400$ mm, a flange width of $b_f = 150$ mm, a flange thickness of $t_f = 12$ mm, and steel grade S273. The ultimate resistance values are presented in tabular form in the *Appendix (*models marked with an * encountered numerical difficulties, preventing completion of the analysis), while the influence of the load application length on factor k is shown in *Figure 7.*

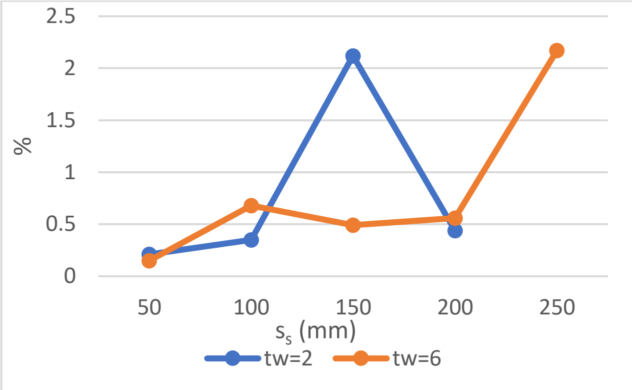


Figure 7: Influence of s_s on k

The results shown in the diagram indicate that the load application length has no pronounced influence on factor k. For both analysed web thicknesses, only minor variations are observed, with no clear trend.

2.2.6. Influence of Flange Width b_f on Factor k

The flange width was varied from 100 mm to 360 mm, while two characteristic web thicknesses were considered: $t_w = 2$ mm and $t_w = 6$ mm. The analysis was carried out on an I-girder with a spacing between transverse stiffeners of $a = 750$ mm, a web depth of $h_w = 400$ mm, a flange thickness of $t_f = 12$ mm, and steel grade S275. The ultimate resistance values are provided in the *Appendix* (models marked with an * encountered numerical difficulties, preventing completion of the analysis), while the influence of flange width on factor k is shown graphically in *Figure 8*.

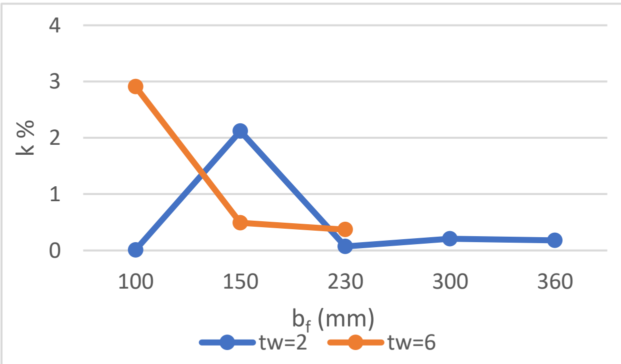


Figure 8: Influence of b_f on k

It can be concluded that flange width has no pronounced influence on the change in ultimate resistance resulting from restrained block rotation. For both analysed web thicknesses, only minor variations are observed, with no clear trend.

2.3. ANALYSIS OF THE INFLUENCE OF PARAMETER β

The results of the parametric analysis showed that factor k depends on the combination of web thickness, flange thickness and web depth. These results indicate that the influence of these parameters cannot be considered independently, but rather through their mutual relationship. In the literature, the relationship between the torsional stiffness of the flange and the bending stiffness of the web is described by parameter β in *Eq. (2)*, as defined by Lagerqvist [2].

$$\beta = \frac{bf \cdot tf^3}{hw \cdot tw^3} \tag{2}$$

For all analysed numerical models, the values of parameter β were determined and are provided in the *Appendix*. The relationship between parameter β and factor k is shown graphically in *Figure 9*.

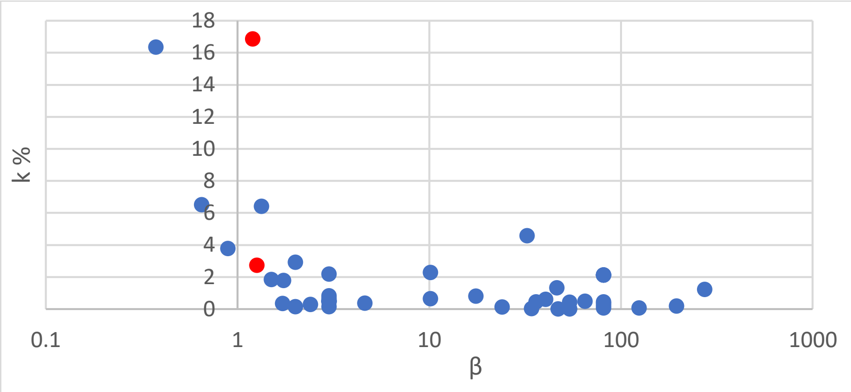


Figure 9: Relationship between Parameter β and Factor k

It can be observed from the diagram that there is no unambiguous relationship between parameter β and factor k. Models with similar or nearly identical values of parameter β exhibit significantly different values of factor k (red marker in the diagram). Specifically, for $\beta = 1.2$, k is 16.85%, whereas for $\beta = 1.265$, it is 2.73%. This confirms that parameter β is not sufficient to describe the influence of loading block boundary conditions on the ultimate resistance of patch-loaded I-girders.

3. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The conducted parametric analysis established that the boundary conditions of the loading block can significantly influence the ultimate resistance of patch-loaded I-girders.

The most pronounced influence was observed for variations in web thickness, flange thickness and web depth, whereas the influence of steel grade, flange width and load application length was considerably less pronounced.

The results showed that the influence of web thickness, flange thickness and web depth cannot be considered independently, but rather through their mutual relationship.

Parameter β is not sufficient to describe the influence of loading block boundary conditions on the ultimate resistance of patch-loaded I-girders.

The obtained results provide a basis for future research aimed at defining a new parameter that would more reliably describe the influence of loading block boundary conditions on the ultimate resistance of patch-loaded I-girders.

Future research should be extended by including the spacing between transverse stiffeners in the parametric analysis, due to its influence on the ultimate resistance and failure mechanism of patch-loaded I-girders.

APPENDIX

Influence of t_w on k					
t_w	t_f	$F_{UR3=0}$ (kN)	$F_{UR3\neq0}$ (kN)	k (%)	ß
2	6	61.93	62.33	-0.64	10.12
3	6	117.15	118.12	-0.82	3.00
4	6	178.59	173.84	2.73	1.26

5	6	242.65	227.85	6.50	0.65
6	6	305.85	262.88	16.34	0.37
2	18	75.41	74.49	1.23	273.37
3	18	143.47	143.39	0.06	81.00
4	18	224.31	224.35	-0.02	34.17
5	18	313.72	311.19	0.81	17.49
6	18	408.85	399.76	2.27	10.12
Influence of t_f on *k*					
t_f	t_w	$F_{UR3=0}$ (kN)	$F_{UR3\neq0}$ (kN)	k (%)	ß
6	2	61.93	62.33	-0.64	10.12
8	2	64.90	64.98	-0.12	24.00
10	2	67.43	67.43	0.00	46.87
12	2	67.82	69.29	-2.12	81.00
18	2	75.41	74.49	1.23	273.37
6	6	305.85	262.89	16.34	0.37
8	6	331.72	319.66	3.77	0.89
10	6	351.85	345.73	1.77	1.74
12	6	366.55	364.77	0.49	3.00
18	6	408.85	399.76	2.27	10.12
Influence of f_y on *k* for Variable t_f					
f_y	t_f	$F_{UR3=0}$ (kN)	$F_{UR3\neq0}$ (kN)		k (%)
235	6	105.48	106.21		-0.69
273	6	117.15	118.12		-0.82
355	6	140.12	141.64		-1.07
440	6	161.39	162.29		-0.55
235	18	129.31	129.26		0.03
273	18	143.65	143.39		0.18
355	18	171.23	171.72		-0.28
440	18	199.79	197.42		1.20
Influence of f_y on *k*, for Variable t_w					
f_y	t_w	$F_{UR3=0}$ (kN)	$F_{UR3\neq0}$ (kN)		k (%)
235	2	62.89	62.93		-0.07
273	2	67.82	69.29		-2.12
355	2	80.18	81.79		-1.97
440	2	92.84	93.28		-0.48
235	6	324.49	314.84		3.07
1273	6	366.55	364.77		0.49
355	6	448.38	447.03		0.30
440	6	527.16	525.05		0.40
Influence of h_w on *k*					
h_w	t_w	$F_{UR3=0}$ (kN)	$F_{UR3\neq0}$ (kN)	k (%)	ß
400	2	67.82	69.29	-2.12	81.00
500	2	71.32	71.67	-0.49	64.80
600	2	72.22	71.92	0.42	54.00
700	2	71.69	70.76	1.31	46.28
800	2	70.66	70.23	0.61	40.50
900	2	70.63	70.31	0.45	36.00
1000	2	69.88	66.82	4.58	32.40
400	6	366.55	364.91	0.45	3.00
500	6	379.71	378.65	0.28	2.40
600	6	388.34	388.89	-0.14	2.00
700	6	394.72	396.09	-0.35	1.71
800	6	391.49	384.45	1.83	1.50
900	6	386.50	363.25	6.40	1.33

1000	6	382.32	327.18	16.85	1.20
Influence of s_s on *k*					
s_s	t_w	$F_{UR3=0}$ (kN)	$F_{UR3\neq0}$ (kN)	k (%)	ß
50	2	57.43	57.31	0.21	81.00
100	2	64.06	64.29	-0.35	81.00
150	2	67.82	69.28	-2.12	81.00
200	2	73.28	72.96	0.44	81.00
250	2	*	*	*	81.00
50	6	291.84	292.29	-0.15	3.00
100	6	329.63	327.38	0.68	3.00
150	6	366.55	364.77	0.49	3.00
200	6	400.34	398.10	0.56	3.00
250	6	435.23	425.98	2.17	3.00
Influence of b_f on *k*					
b_f	t_w	$F_{UR3=0}$ (kN)	$F_{UR3\neq0}$ (kN)	k (%)	ß
100	2	67.72	67.73	-0.01	54.00
150	2	67.82	69.28	-2.12	81.00
230	2	70.77	70.72	0.07	124.20
300	2	71.62	71.77	-0.21	162.00
360	2	72.19	72.32	-0.18	194.40
100	6	353.83	343.81	2.91	2.00
150	6	366.55	364.77	0.49	3.00
230	6	377.54	376.16	0.37	4.60
300	6	379.85	*	*	6.00
360	6	*	*	*	7.20

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