

INFLUENCE OF INITIAL DEFLECTIONS ON COUPLED BUCKLING STRENGTH OF UNSTIFFENED SQUARE BOX SECTION COLUMNS

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Although it is well known that initial deflections have a significant influence on coupled buckling strength, their quantitative influence is not clear. In this paper, a series of nonlinear finite element analyses to reveal the quantitative influence of initial deflections on coupled buckling strength are conducted with MSC.Marc. There are nine kinds of combinations about the size of local and overall initial deflections including 1/75, 1/150, 1/450 of the plate width and 1/500, 1/1000, 1/3000 of the column length. In addition, the width-thickness ratio and slenderness ratio parameters are also varied in the parametrical study. Both ranges of slenderness and the width-thickness ratio parameters are from 0.1 to 2.1. As a result, the initial deflection influence coefficient is proposed to describe the quantitative influence of local and overall initial deflections on coupled buckling strength. The numerical results reveal that the coefficient decreases with the increase of initial deflections. The sensitivity of the strength to initial deflections depends on both width-thickness and slenderness ratio parameters. The maximum decrease of 21.4% on load-bearing capacity caused by local initial deflection appears when width-thickness and slenderness ratio parameters equal to 1.2 and 2.1, respectively. Column strength is quite sensitive to overall initial deflection at the slenderness ratio parameter equal to 1.4. The maximum decrease in load-bearing capacity reaches 18.2%.

Keywords: Axial compression, Local and overall initial deflection, Amplitude of initial deflection, Quantitative influence, Initial deflection influence coefficient, Load-bearing capacity.

1 INTRODUCTION

Thin-walled compression members are subject to interactive buckling instability due to high slenderness and width-thickness ratio parameters. And it is well known that initial deflections have a significant influence on coupled buckling strength. Initial deflections consist of local initial deflection on every plate and overall initial deflection on the column. High amplitude of initial deflections will lead to lower load-bearing capacity in most cases.

Many researchers had measured the amplitude of initial deflections of box section columns. In Usami and Fukumoto's (1982) tests, amplitudes of overall initial deflection on 19 specimens were measured. Their maximum is $L/1590$ and average is $L/3850$, where L is the column length. In Kuhlmann and Detzel's (2004) tests, amplitudes of overall initial deflection on six specimens were measured. Their maximum is $L/3560$ and average is $L/2500$. However, these values are

much smaller than those allowed in some specifications such as $L/1000$ of American (AISC 2016), Japanese (JRA 2017) and Chinese (GB 50017 2003) specifications.

Although many tests on coupled buckling strength have been conducted, there are not many studies to evaluate the quantitative influence of initial deflections. In this paper, unstiffened square cross-section columns under axial compression are chosen as a target. Nonlinear finite element models are developed to analyze the coupled buckling strength of columns. Initial deflection influence coefficient is proposed to describe the quantitative influence of local and overall initial deflections on the strength.

2 VALIDATION OF FE MODEL

2.1 Existing Experiment on Unstiffened Box Section Columns

The tests of six columns were carried out in the Laboratory of Otto-Graf Institute, MPA Stuttgart at the University of Stuttgart (Kuhlmann and Detzel 2004). Cross section is presented in Figure 1. The sections consist of 6mm thick plates with a width of 230mm for the webs and 282mm for the flanges by fillet welds. Three kinds of length, 2200mm, 3700mm and 4900mm are considered. The steel grade of the plates is S355 with measured material properties of 390MPa for the yield stress (f_y) and of 187GPa for Young's modulus (E). Two models were prepared for each column, leading to a total of six tests. The columns were tested under the pin-ended condition with the buckling axis being set parallel to the flange plates as shown in Figure 2.

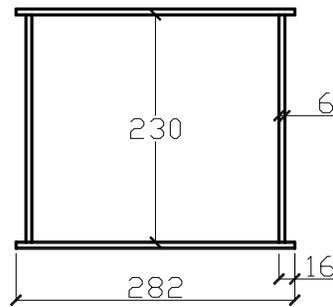


Figure 1. Dimension of cross section.

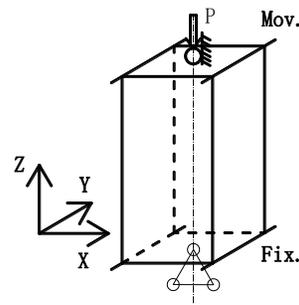


Figure 2. Boundary condition.

2.2 FE Model

The general-purpose FE software MSC.Marc was applied to the numerical analysis on coupled buckling strength of unstiffened box section columns. Thick shell element (No.75) is used in the model. Considering the results of preliminary examination on the influence of mesh size and the convenience of residual stress setting, plates are divided into twenty elements in the width direction with a size of 14.1mm on the flange and of 11.5mm on the web. The von Mises yield criterion is adopted in the analysis. Bilinear model with strain hardening coefficient of $E/100$ is used to describe the material property of S355. Measured material properties are used for the yield stress and Young's modulus. The Poisson ratio is set to 0.3.

Residual stress is assumed to exist in every plate with compressive residual stress in the middle area and tensile residual stress at both sides of the plate as shown in Figure 3 so as to be in self-equilibrium condition. Assumed residual compressive stress is $0.25f_y$, which is the measured maximum of residual stress in the past tests.

Images of both overall and local initial deflection shapes are shown in Figure 4. Half-sinusoidal wave shape expressed by Eq. (1) is assumed for the overall deflection. On the other

and, the double trigonometric function as shown in Eq. (2) is assumed for the local deflection. The amplitude of initial deflections is set to the measured value as shown in Table 1.

$$w_g = A \sin\left(\frac{\pi z}{L}\right) \quad (1)$$

$$w_l = w_{l0} \sin \frac{m\pi z}{L} \cos \frac{\pi x}{b} \text{ Or } w_l = w_{l0} \sin \frac{m\pi z}{L} \cos \frac{\pi y}{b} \quad (2)$$

In the formula, A is the amplitude of overall initial deflection, w_{l0} is the amplitude of local initial deflection, m is the number of half sinusoidal wave giving the minimum buckling strength determined by the aspect ratio of the plate, and b is the plate width.

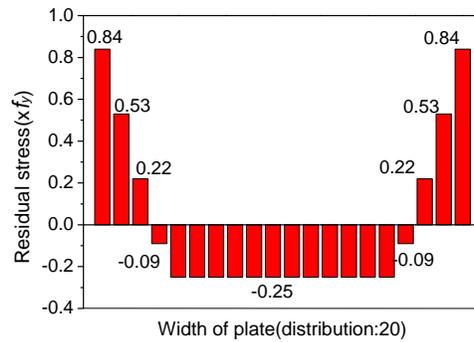


Figure 3. Residual stress distribution in a plate.

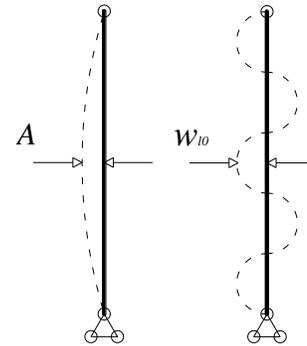


Figure 4. Initial deflection shape.

Table 1. Measured initial deflections.

Initial deflections	S1a	S1b	S2a	S2b	S3a	S3b
Overall initial deflection	$L/2800$	$L/2500$	$L/4000$	$L/4000$	$L/4350$	$L/3700$
Local initial deflection			$b/250$			

2.3 Validation Results

The comparison of ultimate strength between experiments and FE analyses is shown in Table 2. It can be seen that FEA results are slightly lower than test results. This underestimation is considered to be due to the use of the measured maximum initial deflection in the FE models. The average and standard deviation of errors are 3.2% and 1.73%, respectively. Consequently, it can be concluded that the FE models have sufficient accuracy.

Table 2. Comparison of ultimate strength between FE analysis and test.

Specimen	S1a	S1b	S2a	S2b	S3a	S3b	AVG(%)	STDEV (%)
Test results F_T (kN)	2053	2139	2065	2062	2114	2044		
FE results F_F (kN)	2036.1	2035.3	2016.6	2016.6	1987.3	1982.8		
$(F_F - F_T)/F_T$ (%)	-0.82	-4.85	-2.34	-2.20	-5.99	-2.99	-3.2	1.73

3 PARAMETRICAL STUDY

3.1 FE Models of Unstiffened Square Box Section Column

Using the verified models, an extensive numerical study on unstiffened square box section column is carried out. Further numerical models have been defined to cover a range of moderate slenderness and width-thickness ratio parameters shown in Table 3, in which coupled buckling is expected to occur. In addition, the amplitude of local and overall initial deflections is also varied. Table 4 shows nine combinations of the amplitude of initial deflections.

The Combi5 of which the local initial deflection is $b/150$ and the overall initial deflection is $L/1000$ is set as the standard since it is the combination of allowable initial deflections in Japanese design code. Initial deflection influence coefficient (ID influence coefficient) is proposed as the ratio of load-bearing capacity of a combination to that of Combi5 to describe the quantitative influence of initial deflections.

Table 3. Range of main parameters of the numerical specimen.

Parameter	Range of variable
Slenderness ratio parameter λ	0.1-2.1
Width-thickness ratio parameter R	0.1-2.1
Length of the column	1524-32004mm
Thickness of plate	5.28-110.79mm

Table 4. Combinations of amplitude of initial deflections.

	Combi1	Combi2	Combi3	Combi4	Combi5	Combi6	Combi7	Combi8	Combi9
Local	$b/75$	$b/75$	$b/75$	$b/150$	$b/150$	$b/150$	$b/450$	$b/450$	$b/450$
Overall	$L/500$	$L/1000$	$L/3000$	$L/500$	$L/1000$	$L/3000$	$L/500$	$L/1000$	$L/3000$

3.2 Influence of Local Initial Deflection

Results of the models whose R and λ are respectively 0.9 and 1.4 are set as examples to demonstrate the relationship between ID influence coefficient and local initial deflection as shown in Figure 5(a). It can be seen that ID influence coefficient decreases approximately linearly as the amplitude of local initial deflection increases. And the decreasing slope is nearly the same for different amplitudes of the overall initial deflection. Since the decrease of ID initial deflection can be regarded as the decrease of load-bearing capacity, the decrease of load-bearing capacity is 19.2% when the amplitude of local initial deflection increases from $b/450$ to $b/75$.

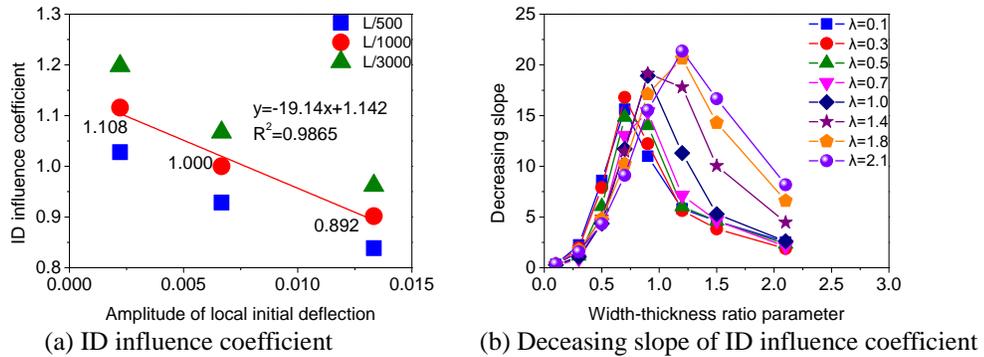


Figure 5. Influence of local initial deflection.

The decreasing slope of ID influence coefficient depends on R and λ . Figure 5(b) and Table 5 show the relationship between the absolute value of the decreasing slope and R -value in the case of the overall initial deflection of $L/1000$. When R is small (i.e., $R \leq 0.5$) or large (i.e., $R > 1.5$), the influence of local initial deflection seems to be slight. In the width-thickness ratio parameter range of 0.7-1.5, column strength becomes comparatively sensitive to local initial deflection.

When λ is small (i.e., $\lambda \leq 0.7$), the influence reaches the maximum with the decreasing slope about 16.79 at R equal to 0.7. It corresponds to the 17.2% decrease of load-bearing capacity. When λ is large (i.e., $\lambda \geq 1.0$), the strength of columns with higher R -value becomes sensitive to the local initial deflection. With R and λ equal to 1.2 and 2.1, respectively, the influence of local initial deflection reaches the maximum with the decreasing slope of 21.37 corresponding to the 21.4% decrease of load-bearing capacity.

Table 5. Decreasing slope caused by local initial deflection (for overall initial deflection of $L/1000$).

R	$\lambda=0.1$	$\lambda=0.3$	$\lambda=0.5$	$\lambda=0.7$	$\lambda=1.0$	$\lambda=1.4$	$\lambda=1.8$	$\lambda=2.1$
0.1	0.32	0.29	0.17	0.18	0.27	0.34	0.37	0.37
0.3	2.25	1.95	1.16	0.88	1.06	1.54	1.77	1.57
0.5	8.60	7.90	6.05	4.43	4.35	4.96	4.83	4.33
0.7	15.63	16.79	14.85	13.04	11.71	11.48	10.24	9.11
0.9	10.99	12.22	14.02	15.37	18.92	19.14	17.13	15.53
1.2	5.81	5.64	6.03	7.14	11.30	17.80	20.63	21.37
1.5	4.59	3.83	4.60	4.64	5.29	10.05	14.29	16.67
2.1	2.52	1.88	2.34	2.08	2.62	4.46	6.60	8.17

3.3 Influence of Overall Initial Deflection

The influence of amplitude of the overall initial deflection on coupled buckling strength is shown in Figure 6(a). ID influence coefficient decreases approximately linearly as the amplitude of the overall initial deflection increases. And the decrement is nearly the same for the different amplitude of local initial deflection. As the amplitude of the overall initial deflection increases from $L/3000$ to $L/500$, the load-bearing capacity decreases by 15.1%.

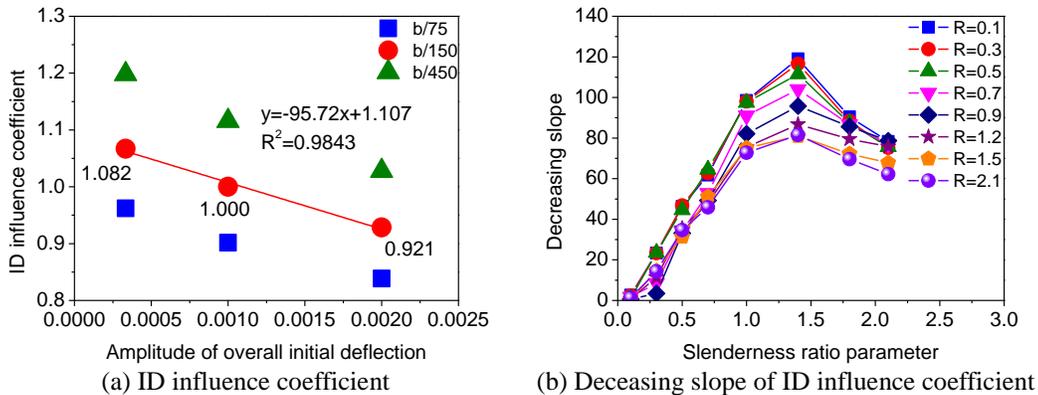


Figure 6. Influence of overall initial deflection.

Figure 6 (b) and Table 6 show the relationship between the decreasing slope and slenderness ratio parameter in the case of the local initial deflection of $b/150$. As the λ -value increases, the decreasing slope increases first, and then decreases after the peak value. In the range of slenderness ratio parameter from 0.7 to 2.1, column strength becomes comparatively sensitive to

overall initial deflection. With λ equal to 1.4, the maximum decreasing slope appears with a range from 81.05 to 119.09.

In addition, the influence of overall initial deflection on coupled buckling strength depends on R . With the decrease of R , the influence of overall initial deflection increases. A probable reason is that column strength is mainly dominated by overall buckling when R is small. With R and λ equal to 0.1 and 1.4, respectively, the influence reaches the maximum with the decreasing slope of 119.09 corresponding to the 18.2% decrease of load-bearing capacity.

Table 6. Decreasing slope caused by overall initial deflection (for local initial deflection of $b/150$).

λ	$R=0.1$	$R=0.3$	$R=0.5$	$R=0.7$	$R=0.9$	$R=1.2$	$R=1.5$	$R=2.1$
0.1	2.59	2.38	0.99	1.73	0.63	0.76	0.47	1.23
0.3	23.34	23.34	23.54	8.54	3.47	11.36	14.54	14.34
0.5	46.39	46.78	44.56	34.02	33.12	35.48	31.43	34.64
0.7	61.71	62.71	64.51	52.84	49.27	48.11	51.05	45.89
1.0	98.57	98.05	97.47	91.04	82.10	75.44	75.04	72.80
1.4	119.09	116.62	111.51	104.04	95.72	86.77	81.05	81.51
1.8	90.42	88.37	87.30	86.64	85.67	79.46	72.24	69.60
2.1	78.32	75.27	75.61	77.06	78.66	75.84	67.76	62.25

4 CONCLUSIONS

Main conclusions of this study can be summarized as follows.

- (i) Coupled buckling strength linearly decreases as the amplitude of local/overall initial deflection increases. The decreasing slope is nearly the same for different amplitudes of overall/local initial deflection.
- (ii) As the width-thickness and slenderness ratio parameters increase, the decreasing slope increases first, then decreases after the peak value.
- (iii) With the width-thickness and slenderness ratio parameters equal to 1.2 and 2.1, respectively, the influence of local initial deflection reaches the maximum with the decreasing slope of 21.37 corresponding to the 21.4% decrease of load-bearing capacity.
- (iv) With the width-thickness and slenderness ratio parameters equal to 0.1 and 1.4, respectively, the influence of the overall initial deflection reaches the maximum with decreasing slope of 119.09 corresponding to the 18.2% decrease of load-bearing capacity.

In the future, formulae to evaluate the quantitative influence of local and overall initial deflections will be proposed based on abundant FEA results.

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