Effect of corrosion on the buckling of steel angle members – experimental study

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Abstract

The aim of this work is to study the effect of corrosion on the buckling behaviour and resistance of corroded steel angle section members. The influences of the corrosion location and the loss of cross-section are studied by experimental investigations, where the corrosion is modelled by artificial thickness reduction. Compressive buckling tests are carried out on twenty-four specimens. Different corrosion damages are modelled, like uniform, pitting and local corrosion in the specimens. The buckling behaviour and the relationship of the corrosion reduction and the resistance decrease are determined.

1 Introduction

1.1 General

Every structure is exposed to the influence of different environment and tends to suffer various types of damage as they get older. The steel structures such as truss bridges, transmission line towers and other structures can be corroded significantly, because of the different aggressive environmental and weather circumstances and due to the inadequate maintenance. Recently several bridges in Hungary had to be repaired due to the damages caused by corrosion. In the case of the Margaret Bridge in Budapest, the inadequate maintenance caused serious corrosion; several members of the stiffener frame/bracing system corroded, as shown in Fig. 1(a). In the case of Liberty Bridge – another Danube bridge of Budapest – the corrosion caused big loss of cross-section, leading to failure of a compression member, as it is illustrated in Fig. 1(b). Note that the corroded member shown in the figure was made of wrought steel.
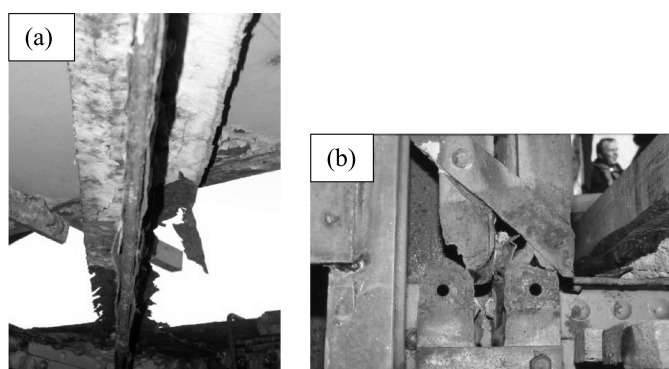

Fig. 1. Corroded structural details in (a) Margaret Bridge and (b) Liberty Bridge

Corrosion can be observed in different places and sizes of the corroded members. During the reparation of the bridge structures it is essential to determine the behaviour and resistance reduction of these members. It is also necessary to decide, that the corroded members have to be replaced or can be strengthened. The codes and standards usually do not give detailed suggestion how the corroded members, connections and structures can be assessed. Eurocode 3 [1] and other major standards such as CAN/CSA, AISC, ASCE recommend to apply average cross-

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section reduction [2] in the prediction of the resistance. Because of the lacking of detailed instructions it may be complicated to estimate the decrease of the resistance of a corrosion damaged member, especially if the damage is not uniform along the member. The corrosion can lead to significant thickness reduction and change in cross-section classification [1], therefore ultimate behaviour can be complicated as typical in thin-walled structural elements [3].

1.2 Previous studies

Appearance, level and location of corrosion may be very different in structures, therefore these effects are widely studied. Beaulieu et al. [2] investigated steel angle members corroded by galvanic process. The main studied parameters in this work were the slenderness, the width-to-thickness ratio and the level of corrosion means cross-section reduction. The specimens were experimentally investigated in truss structure under eccentric compression. The failure modes and the compressive resistance were determined and compared to analytical results. In addition several other studies were completed on the effect of corrosion what proves the importance of the subject and not only in civil engineering structures. Researchers investigated e.g. corroded beams [4], sheared plates [5], compressed plates [6] and pitting corrosion in ships [7]. In these studies the resistance reduction and the ultimate behaviour of the corroded members were determined. The connections, the bolts and rivets also can be corroded; in [8] the durability of the corroded connection is examined. In the previous studies the different types and location of corrosion are not investigated on corroded angle members, what is the subject of the current research.

1.3 Purpose and scope

The experimental work detailed in this paper focuses on the stability behaviour and the compressive buckling resistance of corroded angle members. The aim is to find the tendencies of the effect of different location and size of corrosion on the buckling phenomenon and resistance. The changes in the resistance of various cases are studied. It is planned to determine the local and the global failure modes as well as the post-buckling yield mechanism on the corroded members. The corrosion is considered by loss of cross-section applying artificial thickness reduction. The behaviour and the resistance of the corroded members are compared to the reference non-corroded members and standard based design resistances.

2 Experimental program
2.1 Specimens and test set-up

Compressive buckling tests are carried out on 24 steel angle section specimens, where the corrosion is modelled by artificial reduction of thickness in the legs by milling process. The size of the section of the specimens is 40×40×4 mm, while the length of the member is 790 mm. The sizes of the members are selected to study the buckling behaviour of the member resulting in a 1.25 non-dimensional slenderness. In the specimens different corrosion locations and material loss ratios are applied. The tests are divided into three groups according to the modelled corrosion: uniform, pitting and local. In addition, two specimens (O1, O2) without damages are investigated and are referred as original or non-corroded members. The details of the corroded specimens with the modelled corrosion locations and the shapes are summarised in Tables 2–4. The corroded areas are marked with black colour.

In several experimental studies [7, 9] the corrosion is modelled as a thickness reduction and parts of the member or the thickness were eliminated artificially. In numerical investigations also used thickness reduction for modelling the effect of corrosion [4–6]. In the applied milling process the machine has got a spinning mill head and this process does not change the material properties of the steel member.

The t_{corr} means the thickness of the corrosion. The effective specimen dimensions and the thickness of the members are measured on each leg at ten locations with mortise gauge. The A_{corr} characteristic is introduced as the average corrosion volume reduction; it is calculated as the ratio of the corroded volume comparing to the total original volume of the specimen. The maximal cross-section reduction (M_{corr}) is interpreted as the ratio of the maximal cross-section reduction in the member compared to the gross area. A_{corr} and M_{corr} values are calculated on the basis of the measured dimensions and detailed in Tables 2–4.

The cross-section is classified by the width-to-thickness (b/t) ratio of the legs according to Eurocode 3. In the case of the non-corroded members the class of the cross-sections is (the b/t ratio is 10). The class of the cross-section of all corroded members is 4 (with different b/t ratios).

Tensile coupon tests are carried out to determine the material properties of the specimens. The measured average material properties of three tests are shown in Table 1. Material I and II mark the two different materials applied in the specimens. These codes are shown in parentheses after the identification of the specimen in Tables 2–4.

Tab. 1. Material properties

Material	f_y [N/mm^2]	f_u [N/mm^2]
I	335	460
II	357	475

In the test set-up the support is hinge connection in the centre of gravity of the cross-section. Bearing ball is applied on the end-plate of the specimen in the test arrangement. The support is always applied in the centre of gravity of the original, non-corroded cross-section, with some random, unavoidable eccentricities. The differences between the original and corroded cross-section result in further eccentricity in the loading of the corroded members. Load cell is applied to measure the load and the horizontal and vertical displacements are measured by pulley systems with displacement transducers between the head of the
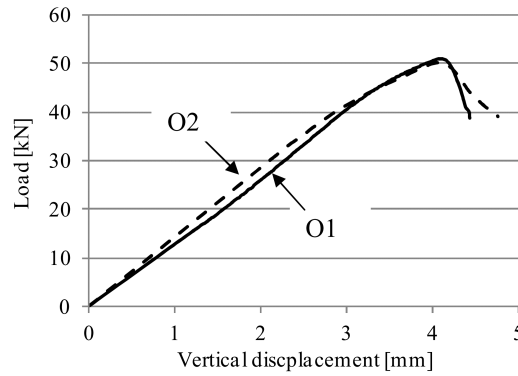
Fig. 2. Test setup and global failure mode; load – displacement curves

loading machine and in the half of the member length, respectively. More details on the measurement system can be found in [10].

2.2 Uniform corrosion specimens

In the case of uniform corrosion the same cross-section reduction is applied along the length of the specimen (total or partial length). Members of this group are signed from A1 to A11 in Table 2. Specimen A1 is the basic case: both of legs are reduced along the whole length. Different corrosion positions are applied within the cross-section with similar volume reduction (A_{corr}) in A2 – A6 members. In A7 – A8 specimens the effect of corrosion on the edges and in the middle of the members are analysed; the corroded surface and A_{corr} are similar to A2 – A6 specimens but the M_{corr} value is different. In A9 - A11 members different corrosion arrangements in both legs along the length are applied with the same A_{corr} value.

2.3 Pitting corrosion specimens

Specimens P1 - P4 model the pitting corrosion as shown in Table 3. In this case the t_{corr} parameter means the depth of the pits. In the formation of the corrosion pattern the experiences of previous studies are applied [7, 9], with two different pit diameters: $d_1 = 12mm$ and $d_2 = 25mm$.

2.4 Local corrosion specimens

Table 4 contains the members with localized, highly corroded cross-section reduction, with lower A_{corr} and higher M_{corr} values comparing to the A type specimens. Specimens L1 – L3 are applied to observe the effect of the local corrosion position along the member. In L1, L4 and L5 members A_{corr} are the same with different M_{corr} ratios. L6 and L1 specimens are identical, but in L6 significant initial imperfections are applied. The thickness reduction in specimen L7 is changing along the element; the biggest thickness decrease is 80% in one of the legs at the edge and the maximal cross-section reduction is approximately 50%.

3 Experimental behaviour

The non-corroded members give the base of comparison in behaviour. In the followings first the ultimate failure mode of the non-corroded and then the corroded members are discussed.

3.1 Non-corroded members

In the case of O1 and O2 members the observed failure mode is global flexural buckling about the weak axis. The yield mechanism is developed at the half-length of the member according to the expectation. In Fig. 2 the test setup and failure mode can be seen, together with the load – vertical displacement curves regarding to O1 and O2 non-corroded members. In case of O1 member the design buckling resistance is 40.18 kN and in case of O2 member it is 40.76 kN, according to Eurocode 3 design method.

3.2 Uniform corrosion specimens

In the case of uniform corroded members the same failure mode, flexural buckling is observed, as in the case of non-corroded cases. As a typical example, the load – horizontal displacement curve of A10 specimen is shown in Fig. 3. The shape of the curve is similar to the original members having smaller ultimate load of the corroded specimen.

3.3 Pitting corrosion specimens

The pitting corrosion members had also global buckling mode. The effect of the whole-length uniform and the pitting corrosion on the behaviour is similar. The load – horizontal displacement curve of P1 specimen is illustrated in Fig. 3. Note that the initial stiffness is bigger in this specimen, what can be explained by the smaller, randomly resulted eccentricity.

3.4 Local corrosion specimens

The failure mode of the specimens with local corrosion is either global flexural buckling or local buckling in the reduced cross-section part of the member. The local buckling occurred in all cases in one leg. In several cases after reaching the

Tab. 2. Uniform corrosion specimens

Specimen	Location of corrosion	t_{corr}	A_{corr} [%]	M_{corr} [%]	b/t
A1 (I)		1 mm	29.0	29.0	13.3
A2 (I)		1 mm	12.8	12.8	13.3
A3 (I)		1 mm	11.7	11.7	13.3
A4 (I)		1 mm	14.7	14.7	13.3
A5 (I)		1 mm	12.7	12.7	13.3
A6 (I)		1 mm	18.8	18.8	13.3
A7 (I)	170 450 170	1 mm	12.4	25	13.3
A8 (I)	170 450 170	1 mm	11.8	25	13.3
A9 (II)		1 mm	13	13	13.3
A10 (II)	395 395	1 mm	13	13	13.3
A11 (II)	195 200 200 195	1 mm	13	13	13.3

Tab. 3. Pitting corrosion specimens

Specimen	Location of corrosion	t_{corr}	A_{corr} [%]	M_{corr} [%]
P1 (II)		d_1 2 mm	9	31.3
P2 (II)		d_2 2 mm	9	32.6
P3 (II)		d_1 2 mm	9	23.4
P4 (II)		d_2 2 mm	9	32.6

Tab. 4. Local corrosion specimens

Specimen	Location of corrosion	t_{corr}	A_{corr} [%]	M_{corr} [%]	b/t
L1 (II)	345 100 345	3 mm	8.3	70	40
L2 (II)	205 100 485	3 mm	8.7	73.5	40
L3 (II)	65 100 625	3 mm	9.0	76	40
L4 (II)	320 150 320	2 mm	8.9	49.8	20
L5 (II)	245 300 245	1 mm	9.9	27.8	13.3
L6 (II)	345 100 345	3 mm	8.6	73	40
L7 (II)	345 100 345	1 mm	23.1	50	40

load-bearing capacity the post-buckling branch of the load-displacement curves shows increasing tendency after a sudden jump in the strength. Figure 4 shows the buckling shape of L1 specimen and the load – horizontal displacement curves of L1 – L3 specimens

Investigating the effect of corrosion positions of L1 – L3, the same buckling behaviour is observed. The character of the load – horizontal displacement curves is the same, as it is illustrated in Fig. 4; decreasing in degree of hardening is observed, when the position is come closer to the end of member. By investigat-
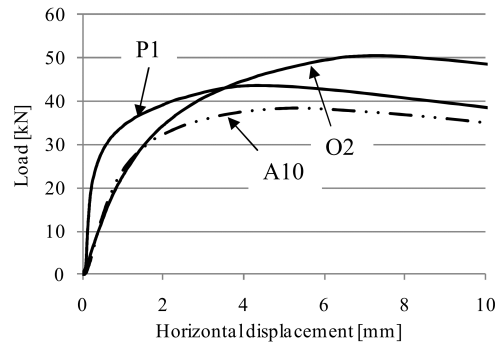
Fig. 3. Load – displacement curves of O2, P1 and A10 specimens

Fig. 4. Local failure mode; load – displacement curves

ing the effect of extension of corroded surface (L1, L4, L5), the same initial behaviour are observed as it is shown on the load – horizontal displacement curves in Fig. 5. The ultimate failure mode is local buckling in L1 specimen and global buckling in L4 – L5 specimens.

Same failure mode and different initial behaviour are observed in the cases of specimens L1 and L6. L1 specimen shows initial global behaviour while L6 shows local phenomenon. Differences are observed in the buckling mode, the load level and the load – displacement curve. As it is expected the corroded specimen with higher initial imperfection (L6) significantly deteriorate the buckling behaviour. In specimen L7 the maximal cross-section reduction is lower than in L6, but approximately the same as in L4. The failure mode of L7 is the same local plate buckling as for L6, since one of the legs has about 80% thickness reduction. The similarity between L6 and L7 also can be observed by comparison the load – horizontal displacement curves and the buckling modes, as shown in Fig. 6.

4 Measured buckling resistances

The experimental buckling resistances of the members are interpreted as the plateau of the load – displacement curve. The buckling resistance values are presented in Tables 5–8. The ta-

bles contain the measured resistance results ($N_{b,m}$) and the ratio of the $N_{b,m}$ and N_c, where compressive strength N_c is calculated by the maximal corroded cross-section area A_c of each members according to the Eurocode 3, Eq.(1).

$$N_c = A_c \cdot f_y \qquad (1)$$

Tables 5–8 contain the ratio of the $N_{b,m}$ and $N_{b0,m}$, where $N_{b0,m}$ denotes the measured resistance of the non-corroded members. The measured resistances of the non-corroded members and the calculated ratios are given in Table 5.

Tab. 5. Results of the tests – non-corroded members

Specimen	$N_{b,m}$ [kN]	$N_{b,m}/ N_{b0,m}$	$N_{b,m}/ N_c$
O1	50.65	1.00	0.49
O2	50.33	1.00	0.45

4.1 Uniform specimens

In Table 6 the measured resistances and the calculated ratios of the uniform corroded specimens are detailed. The resistances show significant scatter. Note that in the cases of A2 and A4 elements no resistance decrease is experienced; it can be explained
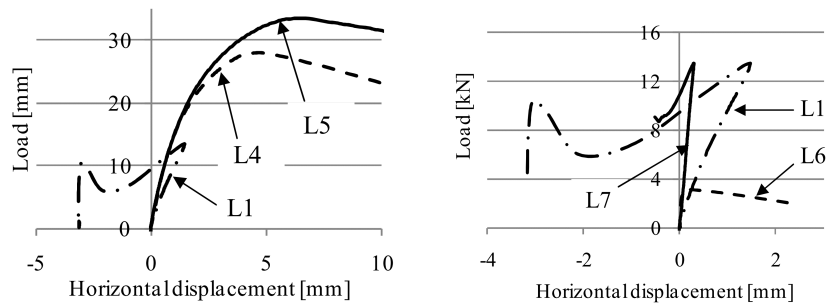
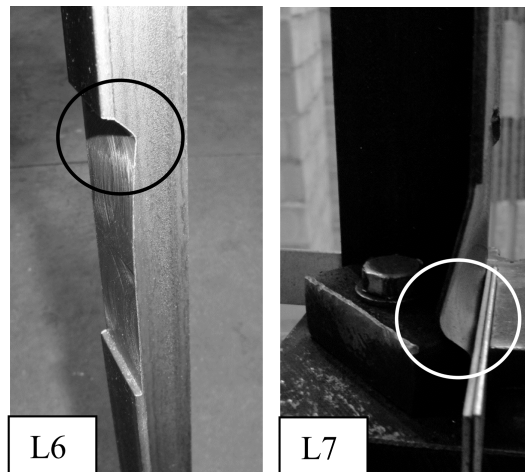**Fig. 5.** Load – displacement curves of local corrosion specimens

Fig. 6. Local buckling modes

by the random eccentricities end restraints of the specimens. In this group A1 member has the maximal A_{corr} value (biggest volume decrease) and this member gives the lowest bound in the evaluations.

On the basis of measured resistances the following observations are made:

- Corrosion on the inner side of the leg (A3) causes bigger resistance reduction, than corrosion on the outer side (A2).

- The specimens A4 – A6 have same corroded surface on different parts of the legs. Corrosion position on the inner part of the legs with symmetrical arrangement (A5) causes approximately 30% resistance decreasing compared to the non-corroded member. This is significantly different from A4 specimen where the corrosion is on the outer part of the legs and the reduction of the resistance is almost negligible. Unsymmetrical corrosion pattern (A6) causes even more reduction in buckling resistance ($\sim$ 33%).

- Corrosion in the middle of the specimen (A8) causes bigger decrease in buckling resistance compared to corrosion close to the supports (A7). The difference is about 10% compared to the non-corroded members.

- A9 – A11 have the same corroded surface with different positions in the specimens. When corrosion is only on one of the legs (A9), the buckling resistance value is bigger, compared to the corrosion on both of the legs. When corrosion

less continuous the buckling resistance decrease is bigger, as it is observed in A10 and A11 specimens.

4.2 Pitting corrosion specimens

Table 7 shows the measured and calculated results of the pitting corroded members. The following observation can be done on the basis of the results:

4.3 Local corrosion specimens

Table 8 contains the results of local specimens. Based on the result the following observations can be done:

- Corrosion position in the middle of the specimen (L1) causes smaller decreasing in buckling resistance, than corrosion location near to the support (L3). The cross-section reduction in these cases more than 50%, and the governing behaviour is local buckling.

- The tendency of the reduction of resistance is approximately linear as the position is closer to the support.

The following observation can be done when specimens have a same volume reduction (A_{corr}) and different cross-section reduction (M_{corr}):

- Widely spread corroded surface with small cross-section reduction (L5) causes lower reduction in resistance compared to localized corrosion with bigger cross-section value (L4).

Tab. 6. Results of the tests – uniform corrosion

Specimen	Location of corrosion	$N_{b,m}$ [kN]	$N_{b,m}/N_{b0,m}$	$N_{b,m}/N_c$
A1		33.2	0.66	0.45
A2		51.02	1.00	0.56
A3		41	0.81	0.45
A4		50.95	1.00	0.57
A5		35.5	0.70	0.39
A6		33.6	0.67	0.40
A7	170 450 170	43.8	0.87	0.56
A8	170 450 170	37.7	0.75	0.48
A9		43.68	0.87	0.45
A10	395 395	38.5	0.76	0.40
A11	195 200 200 195	36.93	0.73	0.38

Tab. 7. Results of the tests – pitting corrosion

Specimen	Location of corrosion	$N_{b,m}$ [kN]	$N_{b,m}/N_{b0,m}$	$N_{b,m}/N_c$
P1		44.72	0.89	0.59
P2		49.23	0.98	0.66
P3		47.16	0.93	0.55
P4		49.6	0.98	0.66

- The tendency is not linear in decreasing; when the specimen has local buckling behaviour, the value of the decrease is bigger. The tendency is shown by the $N_{b,m}/N_{b0,m}$ ratio.

- The effect of initial imperfection is shown by the comparison of L1 and L6 specimens; the increased initial imperfection causes lower buckling resistance (∼20%).

5 Evaluation of resistances

The experimental results of the specimens in three groups are evaluated in this chapter jointly. Figure 7 presents the resistance results plotted in the function of volume reduction (A_{corr}). The mean resistance value is 28.5 kN and the standard deviation is 66% in members with 9% average cross-section reduction. In the case of specimens with ∼ 13% A_{corr} the mean value of the resistances is 40.1 kN and the standard deviation is 13.3%. In the first case the locally corroded members cause the significant scatter, whereas the maximal cross-section decrease is high but the average cross-section decrease is much smaller compared to the uniform specimens. Disregarding locally corroded members the difference in resistance is smaller, but even the maximal decrease is 28% (A11) comparing to the original members. This observation shows that the estimation of the resistance by average cross-section might be uncertain and the A_{corr} parameter alone is not reliable to determine the resistance reduction.
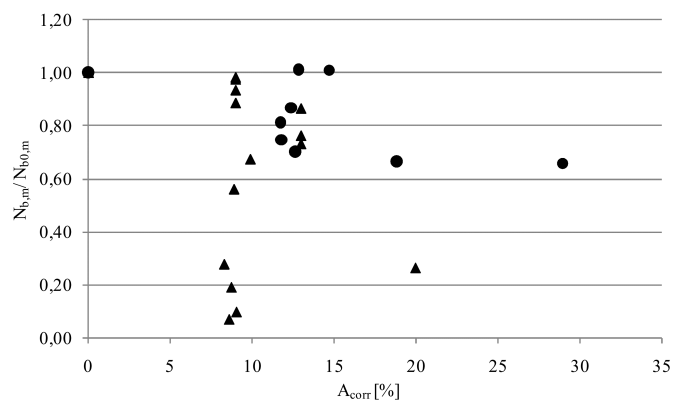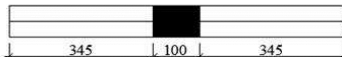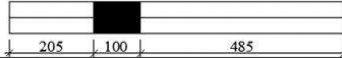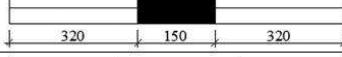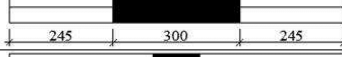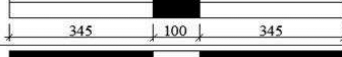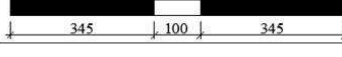

Fig. 7. Experimental results in the function of average cross-section reduction (• f_y=335 N/mm^2; ▲ f_y=357 N/mm^2)

The buckling resistance is compared to the maximal cross-section reduction (M_{corr}) in Fig. 8. The continuous line mark equivalent decrease in resistance and in cross-section reduction. The measured results are on both side of the line. There is no regularity observed in the resistance values. The determined equivalent resistance decrease is not acceptable, particularly in case of the localized corroded members with large discrete cross-section reduction. Application of a maximal cross-section is a better approach than the average cross-section reduction, because the effect of local corrosion is reduced. Despite it

Tab. 8. Results of the tests – local corrosion

Specimen	Location of corrosion	$N_{b,m}$ [kN]	$N_{b,m}/N_{b0,m}$	$N_{b,m}/N_c$
L1	345 | 100 | 345	14	0.28	0.42
L2	205 | 100 | 485	9.6	0.19	0.33
L3	65 | 100 | 625	4.9	0.10	0.18
L4	320 | 150 | 320	28.3	0.56	0.51
L5	245 | 300 | 245	34	0.67	0.42
L6	345 | 100 | 345	3.5	0.07	0.12
L7	345 | 100 | 345	13.3	0.26	0.24

Fig. 8. Resistance and maximal cross-section reduction ($\bullet f_y$=335 N/mm^2; $\blacktriangle f_y$=357 N/mm^2)

is evident from the diagram that this parameter cannot be used as a governing parameter of the resistance reduction.

In the next step of the evaluation the design buckling resistance of compression member is calculated according to Eurocode 3, as shown in Eq.(2). The thickness reduction is supposed to be 1, 2, 3 and 3.5 mm on both of the member legs along the length. Effective characteristics of cross-section are applied to determine the buckling resistance. The broken line shows the results of buckling resistance according to Eurocode 3 in Fig. 9, and Table 9 shows the details of the calculation.

$$N_{b,Rd} = \chi \frac{A \cdot f_y}{\gamma_{M1}} \qquad (2)$$

Almost every case, except the pitting corroded members, the corrosion causes changing in the classification of the cross-section. Therefore in the design buckling resistance calculation the effective cross-section is used, along the whole length. In Fig. 9 results are plotted in the function of M_{corr} and A_{corr}. Estimating the buckling resistances of corroded members by the Eurocode 3 it can be seen that the results are in the safe range in every case if the basis of comparison is M_{corr}. In some cases the estimation too conservative, e.g. for L5 the measured buckling resistance is 28.3 kN, but the code the estimation gives 12.1 kN. If the results are evaluated by A_{corr} in the cases of locally corroded members the measured buckling resistances are smaller than the estimated. However in other cases e.g. for A9 specimen the estimation is also conservative as in the previous case. According to the tests the M_{corr} can be proposed for the estimation of the buckling resistance as a conservative approach.

From the above evaluation of the results it can be concluded that the complex buckling phenomena of the corroded angle members can be described by many parameters, as cross-section reduction, volume decrease, position of corrosion and extension. The completed tests show the tendencies of the behaviour but not enough to derive practically applicable design recommendations.

6 Summary and conclusions

In the research corroded compressed angle sections are studied. Buckling tests are carried out on 24 steel angle section specimens, where the corrosion is modelled by the artificial loss of cross-section in different locations. Uniform, pitting and local corrosions are modelled. The resistance and the behaviour of the steel angle section members are determined and evaluated. On the basis of the experimental study the following conclusions can be made:

- The buckling resistance is reduced by corrosion in different rate: different corrosion position, cross-section and volume reduction causes large scatter in the buckling resistance reduction. The governing buckling mode is global flexural buckling for uniform and pitting corrosion specimens and local plate buckling for locally corroded specimens in the investigated cases.

- Eurocode 3 method for buckling resistance prediction can be used as a conservative estimation by applying the maximal cross-section reduction along the member, considering the changing of the cross-section class due to the decreased thickness.

Tab. 9. Design buckling resistances

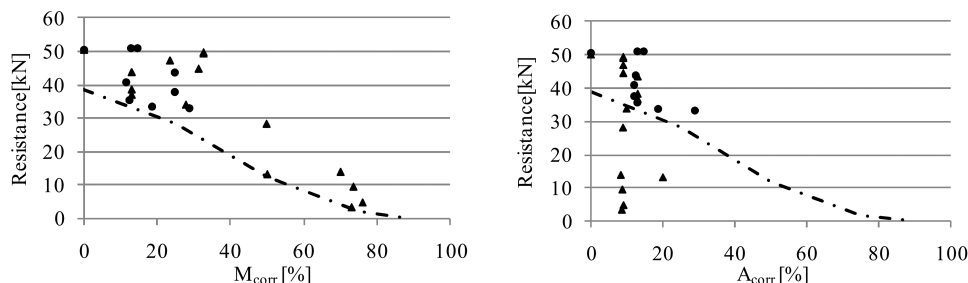| Thickness reduction [mm]	Cross-section reduction [%]	L [mm]	A (A_{eff}) [mm^2]	χ	$N_{b,Rd}$ [kN]
0		840	308	0,38	38,7
1	25	840	226	0,37	28,3
2	50	840	128,3	0,28	12,1
3	75	840	42,94	0,13	1,9
3,5	87,5	840	15,4	0,06	0,31

Fig. 9. Experimental vs. design buckling resistance ($\bullet f_y$=335 N/mm^2; $\blacktriangle f_y$=357 N/mm^2)

- The experimental study is used as a background of a further study by developing advanced numerical model and extending the test results by virtual experiments [11].

Acknowledgement

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