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Buckling capacity of simulated patch corroded tubular columns – laboratory tests

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Abstract. This paper presents the experimental test results for the buckling capacity of tubular columns exposed to simulated unsymmetrical patch corrosion damage. These tests were performed to investigate how the results of these experiments compare with the capacities obtained for the formulae provided in the 2004 revision of NORSOK N-004. Formulae for patch corroded tubular columns are needed in standards and as such it is unfortunate that these formulae are removed from the present revision of the NORSOK N-004 standard. Prior to suggesting introducing these previous formulae in standards, experimental tests to confirm good correlation between experiments and formulae are needed. The tests performed in this work are presented in this paper for 100% (intact columns), 69%, 34% and 0% remaining wall thickness in the patch.

1. Introduction

The vast majority of the infrastructure (offshore platforms, buildings, bridges, etc) in the world is existing and now ageing. This large number of existing structures is of vital importance for society, but they are in many cases degrading and need significant investments for maintenance. Replacement with new structures might be both economically and environmentally unsound. Still, most universities educate students in civil and structural engineering merely in the design of new structures. Fortunately, the University of Stavanger has established a course and research work into the continued use of ageing structures.

However, using ageing structures beyond their original design life also raises several problematic issues. Structures in operation are exposed to conditions of stress and environment that ultimately will degrade them from their initial state and damage will accumulate until the structures may be judged to be no longer fit-for-service. If not withdrawn from further service or being repaired, failure of some kind will eventually occur. Also, the cost of the required maintenance, inspection and repair needed to cope with this deterioration and damage will at some stage become unacceptable compared to the revenue that can be gained from the use of these structures. Hence, it becomes vital to know:

1. how structures change with age,
2. how their condition and other aspects influencing their safety can be determined,
3. how their capacity (strength and fatigue life) can be determined as a result of ageing mechanisms,
4. how any anomalies in the structures should be evaluated,
5. how anomalies found in an existing structure can be repaired and mitigated, and
6. how the integrity management of ageing structures should be performed.

This paper is work performed under item 3 as listed above and is specifically aimed at providing insight into the ultimate capacity of tubular columns in compression with patches representing localized corrosion.

Earlier work on ultimate capacity of tubular columns with patch corrosion includes Ricles et al. and Hebor [1, 2]. These works are the result of laboratory work testing damaged and repaired tubular-profile steel columns under axial compression load. These studies included larger scale tests as previous experiments mostly included diameters below 76 mm. A comparison between the damaged and un-damaged columns showed that the capacity was greatly reduced due to the corrosion. The reduction was reinforced by the fact that an eccentricity arose due to the geometric change as a result of unsymmetrical metal loss. In addition, high stresses occurred in the corroded area.

As we will show in this paper the comparison between documented laboratory tests of ultimate capacity of dented tubular columns compared to NORSOK N-004 [3] formulae is quite promising. In contrast, the comparison between the tests on corroded tubular columns as performed by Hebor [1] was rather disappointing. Hence, it was decided to perform more tests of tubular columns with corrosion damage to provide more data to validate the method provided by NORSOK N-004 [3]. The first stage in this test programme was documented by Hestholm and Vo [4] and the main findings of this programme are given in this paper.

2. Basic buckling theory

In engineering, buckling is a well-known phenomenon. Buckling is an instability by a sudden lateral deflection of a structural element when subjected to compressive loads and can lead to structural failure. Historically, several structural accidents and disasters have occurred due to buckling and instability. The solution to the stability problem is often attributed to Leonard Euler (1707-1783). The solution was based on the following assumptions (Timoshenko and Gere [5]):

- The column material is homogeneous and linearly elastic (that is, it follows Hooke's law)
- The column is perfectly straight and has no imperfections
- The load is applied centrically
- The cross section is constant throughout the length
- The length of the column is considerably longer as opposed to the cross-sectional dimensions

The Euler-formula for buckling capacity is expressed as:

$$N_E = \frac{\pi^2 \cdot EI}{(k \cdot L)^2} \tag{1}$$

where:

N_E is the Euler buckling capacity,
E is the modulus of elasticity of the material,
I is the second moment of inertia of the column,
k is a factor correcting for the effective length of the column (buckling factor),
L is the length of the column.

When using the Euler formula, the maximum compressive load capacity the column will withstand in the elastic regime before becoming unstable is obtained. Being unstable means that the smallest external impact will create an imbalance and the column will experience large lateral deflections and will buckle.

The Euler formula will in practice be of little use to ordinary designs as a column will not be perfectly straight and will have initial imperfections. Further, material will not behave linearly elastic but will rather experience plasticity prior to buckling and especially after buckling. Therefore, in order to determine the capacity of a column both the Euler buckling capacity and the material strength should be taken into account. This means that for columns with low slenderness (L/r where L is the length of the column and r is the radius of gyration), the material strength will be dominant, while for slimmer columns, the Euler formula will apply.

Several empirical formulae for the buckling capacity of columns have been developed. One such formula is the Perry Robertson-formula [6] that is used frequently in civil engineering standards such as Eurocode:

$$\frac{N}{N_d} + \frac{N \cdot (w_0 + e) \cdot \frac{1}{1 - \frac{N}{N_E}}}{M_d} \leq 1.0 \tag{2}$$

where:

N is axial compression loading,
N_d is column buckling capacity,
w_0 is the initial deformation (fabrication allowance),
e is the eccentricity of the axial compression load,
N_E is the Euler buckling capacity,
M_d is moment capacity.

Another commonly used approach to buckling capacity of columns is the Johnson-Ostenfelt correction. This is an empirically based formula that relates the slenderness ratio to the stress that provides the ultimate load required to buckle a column. The formula is based on results from J.B. Johnson from around 1900 [7]:

$$f_{cr} = \phi \cdot f_y$$
$$\phi = \begin{cases} 1 - {\lambda^2}/{2}, & \lambda^2 \leq 2 \\ {1}/{\lambda^2}, & \lambda^2 > 2 \end{cases} \tag{3}$$

where $\lambda^2 = {f_y}/{f_E}$ is the reduced slenderness, $f_E = {N_E}/{A}$ is the Euler buckling stress and f_y is the yield stress.

In addition to global buckling of a column, local buckling of web, flanges or the pipe wall needs to be accounted for in certain circumstances. Global buckling will induce a curvature of the entire length of the element. Local buckling will cause parts of the profile to deform and will weaken the capacity of the local section and thereby the global buckling capacity. Local buckling capacity will in some cases dominate the column's ultimate compressive capacity. Diameter-to-thickness ratio, D/t for tubular sections, is an important factor in classifying the column with regards to its susceptibility to local buckling. A large D/t ratio indicates thin walls and susceptibility for local buckling (slender column), and this needs to be accounted for in the buckling capacity. A lower ratio means that the column is more massive and will not be prone to local instability (compact column). D/t in the mid-range is called a non-compact column.

Steel members used in structures are continuously exposed to various degradation mechanisms and to events that may inflict damage. The typical degradation mechanisms and events are corrosion, fatigue and impacts. In general, degradation mechanisms and events will lead to four different types of effects that need to be accounted for in the calculation of the capacity of deteriorated steel structural members:

- Metal loss and wall thinning (corrosion, erosion, wear, tear, etc.)
- Cracking (fatigue, creep, hydrogen intrusion, etc.)
- Changes to material properties (hydrogen embrittlement, hardening, temperature, etc.)
- Geometric changes (dents from impacts, bowing from impacts, permanent plastic deformation, corrosion, etc.)

This paper intends to study the effect of patch corrosion that will give both metal loss and possible geometrical changes. The metal loss and geometrical changes will reduce the buckling capacity of a damaged column compared to an intact column. The metal loss will result in a reduction in axial and moment capacity in a reduced cross-section. The geometric changes will introduce an eccentricity to the profile if an unsymmetrical change occurs as a result of the patch corrosion as shown in Figure 1. For a simple rectangular section this can be illustrated by three possible corrosion patterns as shown in Figure 2.

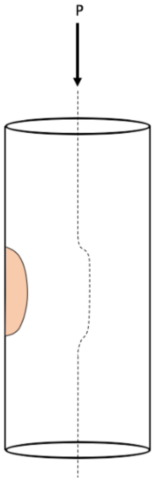

Figure 1. Eccentricity due to unsymmetrical patch corrosion.

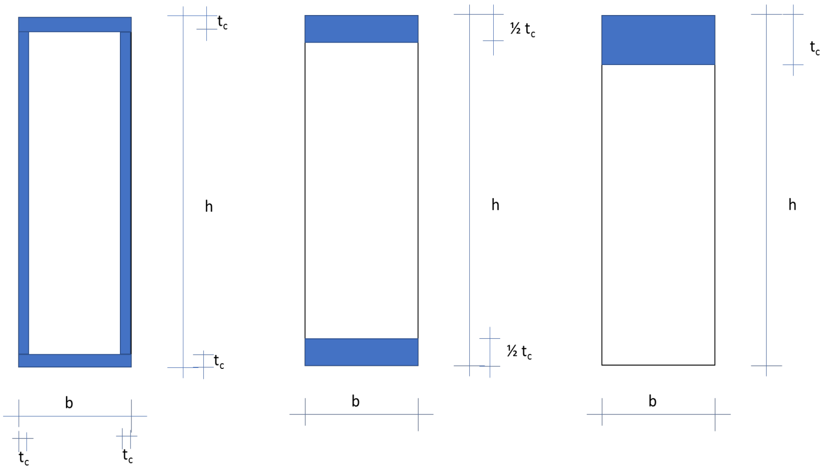

Figure 2. Possible corrosion patterns in a rectangular section.

In the first two corrosion patterns shown in Figure 2, no eccentricity is introduced. However, in the last, unsymmetrical corrosion pattern an eccentricity of $e = t_c/2$ is introduced. Hence, a moment equal to $M = N \cdot e$, where N is the axial force on the column, has to be accounted for in the strength calculations.

In Norway the standards used for design and assessment of structures are Eurocode for land-based structures and NORSOK for offshore structures. In this paper tubular members typical of offshore structures with patch corrosion are studied and, hence, the NORSOK N-004 standard has been used as the basis for capacity calculations.

NORSOK N-004 Rev. 2, October 2004 [3] provides formulae for calculating the capacity of undamaged tubular columns and tubular columns with unsymmetrical corrosion damage based on the formulae for a dented tubular section. In NORSOK N-004 the corrosion is illustrated by an equivalent dent (section 10.6.2.2).

The buckling capacity of an undamaged tubular column in NORSOK N-004 is given by:

$$N_{Sd} = \frac{f_c \cdot A}{\gamma_m} \tag{4}$$

where:

f_c is the compressive strength given by:

$$f_c = \begin{cases} \left(1{,}0 - 0.28\bar{\lambda}_0^2\right) \cdot f_y & for\ \bar{\lambda}_0 \leq 1{,}34 \\ \dfrac{0.9}{\bar{\lambda}_0^2} \cdot f_y & for\ \bar{\lambda}_0 > 1{,}34 \end{cases}$$

λ_0 is the column slenderness parameter given by: $\lambda_0 = \frac{k \cdot L}{\pi \cdot r_{gyr}} \sqrt{\frac{f_{cl}}{E}}$

where:

k is the buckling coefficient

L is the length of the column

r_{gyr} is the radius of gyration for the section given by $\sqrt{I/A}$

f_{cl} is the characteristic local buckling capacity

$$f_c = \begin{cases} f_y & \frac{f_y}{f_{cle}} \leq 0.170 \\ \left[\left(1.047 - 0.274 \cdot \frac{f_y}{f_{cle}}\right) \cdot f_y\right] & 0.170 < \frac{f_y}{f_{cle}} \leq 1.911 \\ f_{cle} & \frac{f_y}{f_{cle}} > 1.911 \end{cases}$$

f_{cle} is the characteristic elastic local buckling capacity given by:

$$f_{cle} = 2 \cdot C_e \cdot E \cdot \frac{t}{D}$$

Where C_e is the characteristic buckling coefficient.

The characteristic buckling coefficient C_e is 0.6 if initial deformations are not included and 0.3 if initial deformations are included. Hence, in this paper $C_e = 0.3$ is used.

NORSOK N-004 provides the following formulae for the ultimate buckling capacity of a dented tubular column:

$$N_{Sd} \leq N_{dent,c,Rd} = \frac{N_{dent,c}}{\gamma_M} \tag{5}$$

where:

$N_{dent,c,Rd}$ is the design capacity of the damaged column,
$N_{dent,c}$ is the characteristic capacity of the damaged column, and
γ_M is a partial material factor.

$N_{dent,c}$ can be calculated as:

$$N_{dent,c} = \begin{cases} \left(1{,}0 - 0.28\bar{\lambda}_d^2\right) * \xi_c * f_y * A_0 & for\ \bar{\lambda}_d \leq 1{,}34 \\ \frac{0.9}{\bar{\lambda}_d^2} * \xi_c * f_y * A_0 & for\ \bar{\lambda}_d > 1{,}34 \end{cases} \tag{6}$$

where:

A_0 is the un-damaged section area
$\bar{\lambda}_d$ is the reduced slenderness of the damaged column given by:

$$\bar{\lambda}_d = \sqrt{\frac{\xi_c}{\xi_M}} * \bar{\lambda}$$

where:

$\bar{\lambda}$ is the relative slenderness of the column
$\xi_c \quad = e^{-0{,}08*\left(\frac{\delta}{t}\right)}, \quad for\ {}^{\delta}/_{t} < 10$
$\xi_M \quad = e^{-0{,}06*\left(\frac{\delta}{t}\right)}, \quad for\ {}^{\delta}/_{t} < 10$

where:

δ is the dent depth
t is the thickness of the tubular member

The equivalent dent depth that is intended to illustrate the corrosion damage is given by:

$$\delta' = \frac{1}{2}(1 - cos\left(\pi \frac{A_{corr}}{A}\right) D \tag{7}$$

where:

δ' is the equivalent dent depth
D is the diameter of the tubular column
A is the cross-section area of the tubular column
A_{corr} is the cross-section area of the corroded tubular column

As a patch corrosion may introduce eccentricities causing a local moment the formulae for moment capacity of a damaged tubular also has to be included. According to NORSOK N-004 the ultimate moment capacity of dented tubular member can be written as:

$$M_{sd} \leq M_{dent,Rd} = \begin{array}{ll} \xi_M \cdot M_{Rd} & if\ dented\ area\ is\ in\ compression \\ M_{Rd} & otherwise \end{array} \tag{8}$$

where:

$M_{Rd} = \frac{f_m W}{\gamma_M}$ is the design moment capacity of the undented tubular member,
$M_{dent,Rd}$ is the design moment capacity of dented tubular member,
M_{sd} is the design moment capacity,
f_m is the characteristic stress in bending,
W is the elastic moment of inertia of the section,
γ_M is the material partial factor.

where:

$$f_m = \frac{Z}{W} f_y \qquad for\ \frac{f_y D}{Et} \leq 0.0517$$

$$f_m = \left(1.13 - 2.58\left(\frac{f_y D}{Et}\right)\right)\left(\frac{Z}{W}\right) f_y \qquad for\ 0.0517 < \frac{f_y D}{Et} \leq 0.1034$$

$$f_m = \left(0.94 - 0.76\left(\frac{f_y D}{Et}\right)\right)\left(\frac{Z}{W}\right) f_y \qquad for\ 0.1034 < \frac{f_y D}{Et} \leq 120\frac{f_y}{E}$$

where:

Z is the plastic moment of inertia of the section

The combination of axial compression and bending moment that the tubular column will experience when exposed to un-symmetric patch corrosion needs to be combined when checking the capacity. NORSOK N-004 gives an interaction formula based on the Perry Robertson formula presented earlier. The capacity of the tubular column is seen as acceptable if the following formula is satisfied:

$$\frac{N_{Sd}}{N_{dent,c,Rd}} + \sqrt{\left(\frac{N_{Sd}\Delta y_2 + C_{m1}M_{1,Sd}}{\left(1 - \frac{N_{Sd}}{N_{E,dent}}\right) M_{dent,Rd}}\right)^{\alpha} + \left(\frac{N_{Sd}\Delta y_1 + C_{m2}M_{2,Sd}}{\left(1 - \frac{N_{Sd}}{N_E}\right) M_{Rd}}\right)^{2}} \leq 1.0 \tag{9}$$

where:

$$\alpha = \begin{cases} 2 - 3\frac{\delta}{D} \ldots if\ the\ damaged\ area\ is\ in\ compression \\ 2 \qquad\quad \ldots if\ the\ damaged\ area\ is\ in\ tension \end{cases}$$

N_{Sd} is the design axial force exposed to the tubular column,
$M_{1,Sd}$ is the design moment about the axis parallel to the damage,
$M_{2,Sd}$ is the design moment about the axis perpendicular to the damage.
$N_{E,dent} = \pi^2 \frac{EI_{dent}}{(kl)^2}$
k is the effective length factor,
I_{dent} is the second moment of inertia for the damaged cross-section $= \xi_M I$
I is the second moment of inertia for the undamaged cross section,
Δy_1 is the member eccentricity perpendicular to the dent,
Δy_2 is the member eccentricity in-line to the dent,
C_{M1}, C_{M2} is moment reduction factors provided by NORSOK N-004

In the tests the columns are subject to axial compression exclusively. Any resulting moment is due to the eccentricity due to patch corrosion. Hence, the interaction formulae by setting the moment reduction factor equal to 1.0 can be simplified to $M_{1,Sd} = N_{Sd}\Delta y_2$ providing the following formula for capacity check:

$$\frac{N_{Sd}}{N_{dent,c,Rd}} + \sqrt{\left(\frac{N_{Sd}\Delta y_2}{\left(1-\frac{N_{Sd}}{N_{E,dent}}\right)M_{dent,Rd}}\right)^{\alpha}} \leq 1.0 \qquad (10)$$

3. Comparison of existing tests and NORSOK N-004 formulae

A comparison of the results from Hebor [1] and the calculated capacities according to NORSOK N-004 [3] for patch corroded columns in compression are shown in Figure 3. The tests performed by Hebor [1] included specimens with a diameter of 218 mm and a thickness ranging from 3.4 to 6.5 mm with thickness loss ranging from 0% to 100%. As can be seen in Figure 3 the results from Hebor [1] indicate significantly larger capacity compared to the calculation formulae in NORSOK N-004.

A similar comparison was performed where results of experiments documented in the existing literature of tests of dented tubulars were compared to the NORSOK N-004 formulas [8-19]. In order to achieve reasonably similar results from the two sources (the NORSOK N-004 formulas and the experimental results) the added moment due to the eccentricity introduced by the deformation of the dented section had to be included from NORSOK. This fact is not clearly stated in the standard. After the inclusion of the moment due to the eccentricity introduced by the dented section the comparison between the experimental results and capacity based on NORSOK N-004 was as shown in Figure 4, indicating a reasonable compliance.

Due to the lack of similarity in the comparison with the tests performed by Hebor [9] and NORSOK N-004 calculations for patch corroded columns it was decided to perform more tests of tubular columns with simulated corrosion damage to provide more data for the validation of the NORSOK N-004 formulae.

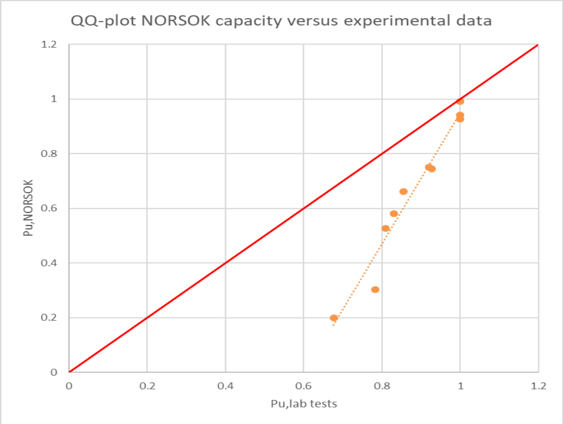

Figure 3. A comparison of the results of the tests performed by Hebor [9] and calculations according to NORSOK N-004 [3].

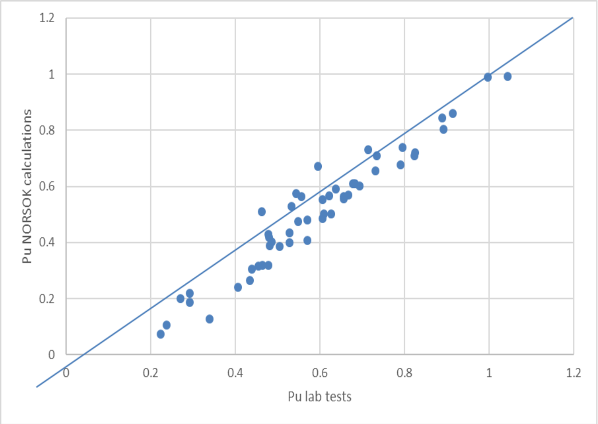

Figure 4. Comparison between capacity of dented tubular columns according to experiments (x-axis) and calculations according to NORSOK N-004 [3] (y-axis).

4. Overview of test programme

The test equipment used was limited by a 400 kN maximum compression force and a maximum specimen length of 2 m. The strength of the steel was selected to S235 and the test specimens used were 70 mm x 2.9 mm steel pipes with a length of 1.5 m. The slenderness of the selected columns was 63 and the outer diameter to thickness ratio D/t was 24.1 which is a reasonable value compared to tubular columns used in several structural applications.

The material certificate of the longitudinal welded steel tubes specified a Re min. of 235 MPa, mechanical test value Re of 280.4 MPa and a corresponding tensile strength Rm of 391.7 MPa. Five (5) independent mechanical tension tests were performed in the UiS test laboratory from test specimens taken directly from the received tubulars as shown in Figure 5. These tests indicated a mean value of the yield strength of 340 MPa.

The test machine for the buckling test is the TONI TECHNIK Baustoffprüfsysteme GmbH D-1000. The machine is designed to test bending capacity for beams and hence the machine is not optimized for the testing of columns. However, some modifications were introduced to enable buckling tests of aluminium columns with this machine previously and the same type of setup was used for these tests.

In order to position the tubular column in the test machine two fasteners cups were machined to hold the tubular column in position at each end as shown in Figure 6.

Figure 5. Test specimens from the yield strength test.

Figure 6. Tubular column mounted in test machine.

The test setup was intended to give a column that was fixed in the lower end and simply supported (pinned) in the upper end. Buckling tests of undamaged cross-sections were performed as a calibration test. This calibration test was intended to provide:

- A basis for the ultimate capacity of an undamaged column,
- A check of the buckling mode and hence the correctness of the assumed support condition.

The tests indicated a buckling mode with maximum deflection and buckling failure at L/2 as opposed to the expected 0.7 L if the assumptions for the support conditions were true. This indicated that the column either experienced both supports as pinned or as fixed. Hence, calculations according to NORSOK N-004 have been performed with pinned, fixed and fixed-pinned boundary conditions.

Initial deformation was measured prior to testing by use of a straight-edge. With the available equipment at the UiS laboratory no global initial deformation could be detected. Some small local deformation (ovalities and changes in diameters) was indicated in some measurements, but these were of minor nature and not included in further evaluations.

The damage area simulating patch corrosion was selected to be 70mm in height and 70mm along the arc length of the pipe giving an angle of damaged area to be 114.6 degrees. The background for the chosen amount of corrosion damage (wastage) inflicted on the tubulars was based on an attempt to achieve results for a range as wide as possible of capacity reductions (ratio between damaged and un-damaged columns). A range from 1.0 down to approximately 0.4 was achieved in the tests. This was achieved by removing 0.9mm, 1.9mm and 2.9mm by grinding in order to simulate corrosion damage (wastage).

In order to distinguish between the different columns, they were named with the following particulars: *Pipe diameter, wall thickness, damage extent as a percentage of thickness, chronological test number within their group*. As an example, a tube with 1mm remaining thickness is marked as 70-29-34-4, where 70 is outer diameter, 2.9 is material thickness, 34 is percent of remaining thickness and 4 would be the test number within the group. In addition, the tubulars with a simulated through thickness patch corrosion has an "h" or "r" at the end of the identification that indicates whether the corners of the damage are hard or round. Hard corners were cut with angle grinders and round corners were drilled.

The reasoning behind the simulated patch corrosion area was rather pragmatic and an area of DxD where D is the diameter of the pipe seems a reasonable size to start the investigation. The attempt was to have a uniform thickness reduction in this area. However, as can be seen in Figure 7 the grinding process may have left the specimens with some minor variations in thickness.

Grinding was chosen over other possible methods in order to reduce heat and possible changes to the material properties during the process. However, there is still a possibility that some residual stresses were introduced during the grinding process.

Figure 7. Example of tubular column with simulated corrosion damage by grinding.

5. Results of test programme and comparison with NORSOK N-004 calculations

Figure 8 shows the resulting failure mode for 3 of the tests performed. In the cases with 34% and 69% thickness loss it seems like local buckling has occurred. NORSOK N-004 does not indicate the same amount of local buckling as observed in the patch corroded area for the test specimens. However, the local buckling observed may be more prominent for these rather small-scale tests than a more realistic size specimen relevant for the NORSOK N-004 (minimum thickness for NORSOK N-004 formulas is t = 6 mm).

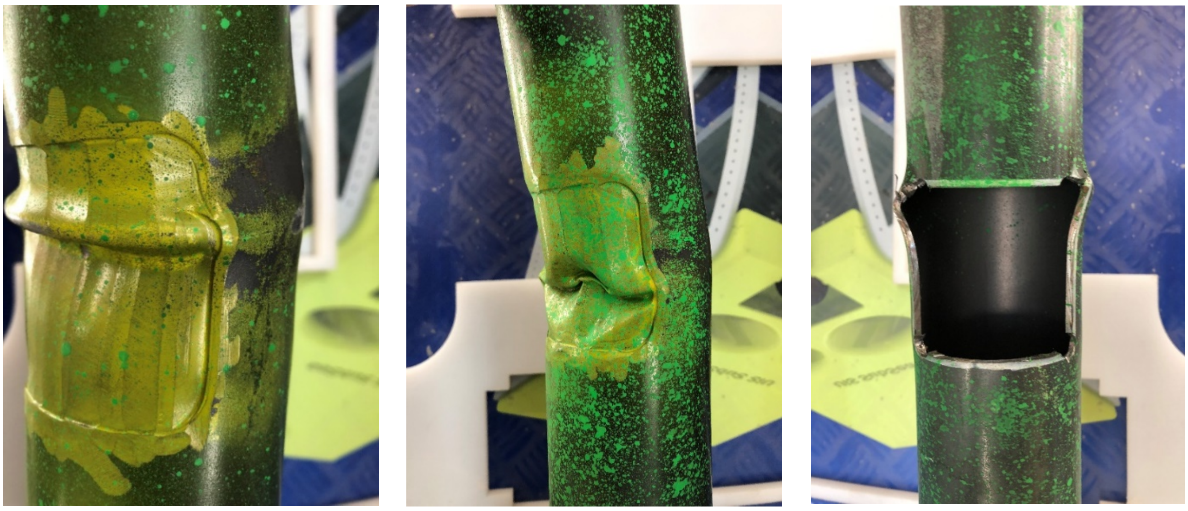

Figure 8. Example of the failure mode of the columns with 34%, 69% and 100% of the thickness "corroded" respectively.

Control measurements of the remaining thickness of the simulated corrosion patches were performed for two specimens. These two specimens were selected for control measurements due to their rather large deviation in their test series. Some deviations from the intended thicknesses were registered and new calculations were performed according to NORSOK N-004 with updated remaining thickness for the specimens with deviations (marked with * in Table 1).

In addition, there were some doubt regarding the straightness of the support cups for the first runs of each series (marked with ** in Table 1). This may have introduced an additional moment in the column that reduced the ultimate capacity slightly. However, a proper estimate of the influence of this effect has not been established.

Figure 9 shows a q-q-plot of measured capacities and capacities according to NORSOK calculations where all values are normalized using the largest measured value of the undamaged column (192.31 kN). Apart from the two results giving significantly lower capacities compared to NORSOK N-004, the estimated capacities of the tubular columns compares reasonably well (bias 1.09 and CoV 17%). For columns with low remaining material thickness (~1 mm) the calculations consistently provide higher capacity than the experiment. This indicates that the calculation method in NORSOK N-004 may underestimate the effect of local buckling. The two largest deviations are found for case 70-29-34-1 and 70-29-34-2 obtaining only 81% and 85% of the calculated capacity respectively.

Table 1. Corrected values for tests and calculations according to NORSOK N-004.

Sample	Damage position	t'	f_u	f_y	P_u NORSOK (partial factors =1.0)			P_u Test
					k=0.5	k=0.7	k=1.0	
70-29-100-1	0	2.9	388.7	343	190.7	180.9	159.9	184.12**
70-29-100-2	0	2.9	388.7	343	190.7	180.9	159.9	191.05
70-29-100-3	0	2.9	388.7	343	190.7	180.9	159.9	192.31
70-29-69-1	975	2 (1.5)	388.7	343		124.0*		145.15**
70-29-69-2	975	2	388.7	343	154.4	145.5	125.9	164.14
70-29-69-3	750	2	388.7	343	154.4	145.5	125.9	158.92
70-29-69-4	750	2	388.7	343	154.4	145.5	125.9	155.34
70-29-69-5	750	2	388.7	343	154.4	145.5	125.9	162.67
70-29-34-1	975	1 (0.4)	388.7	343	78.7*	78.4*	65.9*	63.79**
70-29-34-2	975	1	388.7	343	105.9	101.9	86.7	82.91
70-29-34-3	750	1	388.7	343	105.9	101.9	86.7	99.69
70-29-34-4	750	1	388.7	343	105.9	101.9	86.7	98.08
70-29-34-5	750	1	388.7	343	105.9	101.9	86.7	98.89
70-29-0-1h	975	0	388.7	343	62.7	59.5	53.2	75.43**
70-29-0-2r	975	0	388.7	343	62.7	59.5	53.2	92.97
70-29-0-3r	975	0	388.7	343	62.7	59.5	53.2	81.25

1. Capacities calculated based on NORSOK N-004 is performed by eliminating the safety factors (all safety factors set to 1.0) and applying yield stress values of 340MPa from the tensile tests of the steel used in the tests. Eccentricity of the column due to fabrication misalignment is set to L / 2000 in these calculations.

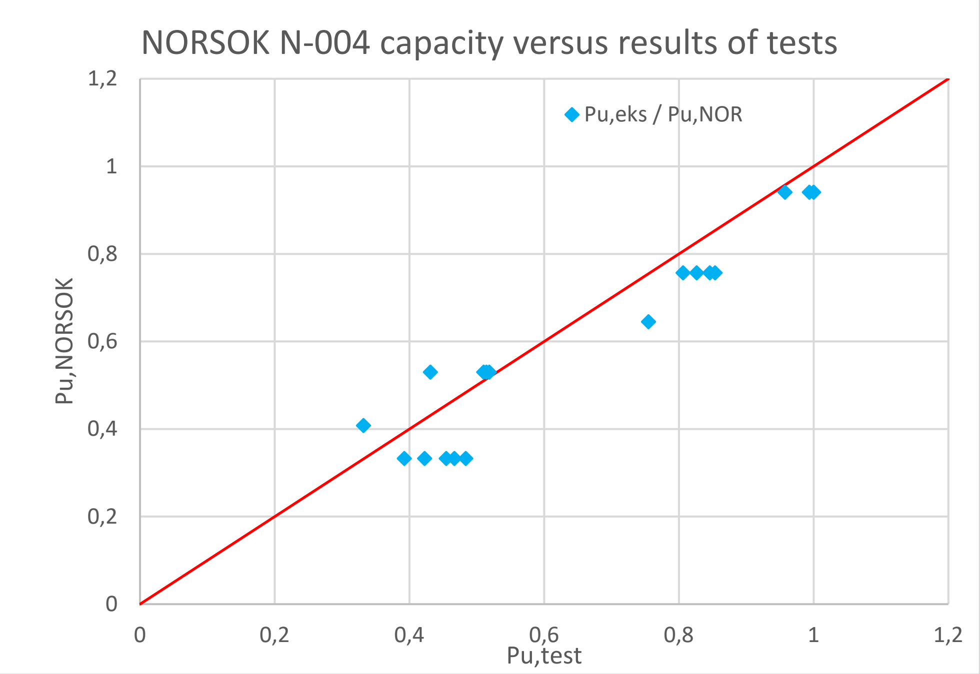

Figure 9. Q-Q plot of results of laboratory tests versus calculated capacities according to NORSOK N-004 [3].

6. Conclusions and recommendation for further work

A set of tests of tubular columns with varying degrees of corrosion thickness (simulated by grinding) has been performed with reasonable results compared to the calculation formulae given in NORSOK N-004 [3]. Several of the tests showed signs of local buckling in the area of patch corrosion. However, the calculation formulae in NORSOK N-004 did not indicate local buckling as being a major factor in the capacity of these specimens. For columns with low remaining material thickness (~1 mm) the calculations consistently provided higher capacity than the experiment. This indicates that the calculation method in NORSOK N-004 may underestimates the effect of local buckling. The two largest deviations were found for case 70-29-34-1 and 70-29-34-2 obtaining only 81% and 85% of the calculated capacity respectively. The dimensions of the specimens used in these tests are rather small (thickness of 2.9 mm) and may be a reason for local buckling being more prominent compared to the prediction by the equations in NORSOK N-004.

Further work in this area is needed, especially more realistic ways of introducing realistic patch corrosion to the specimens. Preferably this should be introduced by means of local accelerated corrosion. This will introduce some uncertainty into the tests as the remaining thickness has to be measured after the corrosion process and most likely after the buckling tests have been performed.

Other vital issues that need further investigation include:

1. The effect of the position of damage (L/2 or 2*L/3) showed no significant difference in the capacity in the tests performed in this work. This seems unrealistic but may be further investigated by more FEM-analysis or by a new series of tests with this as the main purpose to investigate.
2. Boundary conditions are not sufficiently well established in the laboratory experiments. Some of the results indicated an effective buckling length of approximately 0.5 times L (fixed-fixed condition). A test setup that is more in line with the intended support conditions should be used for future tests. A FEM-analysis with the full test rig applying contact elements (between column and “shoe” and between “shoe” and end-plate connected to rig) is a possible way to model and investigate the actual boundary conditions obtained by the actual test set-up.
3. The test specimens are rather small compared to what is normally used in the offshore and building industry. The effect of local buckling may therefore be affected by these rather small-scale test. Test with specimens of more realistic dimensions and various reduced slenderness ratios should be performed at a later stage.
4. All tests in this work were performed with the same rather low slenderness ratio. For future tests specimens with a higher slenderness ratio should be performed.
5. The test setup used in these tests introduced a small rotation to the lower end support as the “cup” was not 100% levelled. After some 4-6 tests the cup loosened and seemed to introduce less rotation, which was also seen in the resulting capacities and load-displacement curves. A test setup that is less sensitive to such irregularities should be used for future tests.

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