Experimental and numerical evaluation of the axial capacity of cracked tubular members

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Abstract. This paper presents the experimental and numerical results for the axial capacity of cracked tubular steel members. Experimental tests of 11 columns in compression with simulated cracks of different sizes, defined as the percentage of the circumference (12%, 23.5% and 38.5%). The crack-tips were further treated by drilling a crack arresting hole. These specimens were then modelled by finite element analysis which were verified to match the experimental test. The DNVGL-RP-C208 standard was used as basis for performing the numerical finite element analysis. In addition, the capacity of the columns was calculated according to the 2004 revision of the NORSOK N-004 standard. The experimental tests indicated that the capacity in compression did not change significantly with the presence of cracks and crack arresting holes. The results from the numerical finite element analysis show a good agreement with the experimental work. However, the compressive capacity according to NORSOK N-004 shows a significant deviation to the safe side.

1. Introduction
A large number of existing offshore structures are an essential part of the infrastructure in the world, and these are of vital importance for the societies where they are being used. In many cases, these are degrading and in need of significant investments for strengthening, maintenance and repair to be safely further used. Replacement with new structures is an option, but replacement might be both economically and environmentally unsound. Structures in operation are exposed to conditions of stresses 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 If these degraded and damaged structures are not withdrawn from further service or being repaired, failure of some kind will eventually occur. In addition, the cost of the 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.

In order to manage existing structures in a safe manner it is vital to know:
1. how structures change with age (including deterioration, damage and load changes),
2. how these changes, particularly to the condition, can be determined,
3. how their capacity can be determined as a result of degradation, damage and other changes,
4. how anomalies found in an existing structure can be repaired and mitigated, and
5. how the integrity of ageing structures should be managed.
This paper is work performed under item 3 as listed above and is specifically aimed at providing insight into the ultimate capacity of cracked tubular members. This work is based on the master thesis by Vågen [1] and the bachelor thesis by Riise [2].

According to Duan, Chen and Loh [3], the capacity of damaged tubular steel members has previously been studied experimentally by several researchers during the 1980s. Non-linear numerical analysis was used by Macintyre and Birkemoe in 1989 in the investigation of axial compression of dented tubular elements [3]. This paper shows a comparison between calculations according to NORSOK N-004 [4] and experimental tests. In addition, the paper shows the method for obtaining calibrated non-linear finite element analysis.

2. Global and local buckling capacity of columns

It is well-known that global and local buckling of columns can lead to structural failure, and historically, several structural accidents and disasters have occurred due to buckling and instability.

A solution technique to the stability problem was developed by Leonard Euler (1707 – 1783), and according to Timoshenko and Gere [5] following assumptions is taken into account: an ideal column, perfectly straight, and compression load applied in the centre. This resulted in Euler-formula:

\[ P_{cr} = \frac{\pi^2 \cdot EI}{L_{eff}^2} = \frac{\pi^2 \cdot EI}{(k \cdot L)^2} \]

where:
- \( P_{cr} \) is the critical load / Euler’s critical load,
- \( E \) is the young’s modulus,
- \( I \) is the second moment of inertia,
- \( L_{eff} \) is the effective length of the column,
- \( k \) is the coefficient which gives the effective length,
- \( l \) is the length of the column.

The Euler formula is the cornerstone for buckling theory. However, it only applies to idealized columns and loading and is not applicable for real columns, as these will include a certain level of imperfection from production and the loading. In reality, the column never suddenly buckles. Instead, they begin to deform ever so slightly immediately after the load is applied. This is known as the second-order effect. Another condition that's not met in reality is the linear elastic behavior of the material. Many practical columns are in a range of slenderness where the buckling portions of the column are no longer linearly elastic, causing a reduction in stiffness due to partial or full yielding at a point on the cross-section with compressive residual stresses. Analysis to determine a realistic maximum capacity of columns in compression needs to include the imperfection, material non-linearity and the effect of residual stresses. Hence, accurate determination of columns’ maximum strength is a complicated process involving numerical integration.

Another failure mode in structural engineering is local buckling, and in certain circumstances, local buckling of web, flanges or the pipe wall can considerably reduce the capacity of structural elements. Unlike global buckling, local buckling causes deformations of parts of the structural element and hence leads to lower capacity. In some cases, local buckling dominates the ultimate compressive buckling capacity of a column. Tubular sections are classified as either slender columns or massive columns, and a factor for the classification of tubular members is the diameter-to-thickness ratio (D/t). Slender columns are more susceptible to local buckling and have a large (D/t) ratio. A compact column has a lower (D/t) ratio and will not be prone to local instability.

NORSOK N-004 (2004) provides the necessary formulae to estimate the ultimate buckling capacity of a dented tubular column and provides formulae for equivalent dents to simulate corrosion damage.
and partially cracked tubular members. The equivalent dent depth for a partially cracked tubular is given by:

\[
\delta' = \frac{1}{2} (1 - \cos \left( \pi \frac{A_{\text{crack}}}{A} \right)) D
\]

where:
- \(\delta'\) is the equivalent dent depth
- \(D\) is the diameter of the tubular column
- \(A\) is the cross-section area of the tubular column
- \(A_{\text{crack}}\) is the crack area

The unfactored ultimate buckling capacity of a dented tubular column is by NORSOK N-004 given by:

\[
N_{\text{dent,c}} = \begin{cases} 
(1.0 - 0.28\lambda_d^2) \cdot \xi_c \cdot f_y \cdot A_0 & \text{for } \lambda_d \leq 1.34 \\
0.9 \frac{\lambda_c^2}{\lambda_d^2} \cdot \xi_c \cdot f_y \cdot A_0 & \text{for } \lambda_d > 1.34 
\end{cases}
\]

where:
- \(A_0\) is the un-damaged section area
- \(f_y\) is the yield stress
- \(\lambda_d\) is the reduced slenderness of the damaged column given by \(\lambda_d = \frac{\xi_c}{\xi_M} \cdot \bar{\lambda}\)
- \(\bar{\lambda}\) is the relative slenderness of the column
- \(\xi_c\) is the yield strength for P235TR1 steel
- \(\xi_M\) is the thickness of the tubular member

3. Experimental tests

The test program consists of 11 columns with different cracks corresponding to a remaining capacity of 25%, 50%, and 75% of an intact column according to the NORSOK N-004 [4]. Further, crack arresting holes with different radii was drilled at the crack ends to replace the sharp crack tip with a rounded profile. The test program also includes six stub-column tests to obtain the material properties.

The test machine and test setup were similar to that of Vo et al [6]. The test setup's attachments were made to only fit tubes with 70 mm diameter and a maximum height of 2 m. Further, the largest cross-sections possible within the machine's restraints were needed to replicate members used in the offshore structures, which led to choosing S235 steel, a relatively low grade. The pipe selected was cold-formed P235TR1 70 x 2.9 mm x 6 m. The specimen length was 1500 mm. These specimens have a D/t ratio of 24.2 and a slenderness ratio of 63. Hence, the failure mode will be global inelastic buckling for the intact column. Such D/t and slenderness ratio is reasonably compared to tubular columns in offshore structures according to Vo et al [6].

The nominal yield strength for P235TR1 steel is 235 MPa and in accordance with Hess et al [7] the mean value for the base metal tests can be expected to be about 20% higher than the nominal yield stress. However, hardening will for cold formed steel increase the yield strength further.
3.1. Testing (test preparation)

3.1.1. Stub-column test. Stub column tests were carried out to obtain the actual material properties. The procedure followed in this test is the American standard AISI S902-13 [8]. Several data can be obtained from such test. For this experiment however, the target was to obtain the stress-strain curve, yield strength and young's modulus of elasticity.

The test consisted of 2 stub column compression tests. The length chosen for the stub columns was 234 mm, as this meets the standard requirements and the test machine capacity. The specimens were cut out 70 mm from the pipe ends with a band saw. Further, the ends were machined in a lathe to meet the end surface flatness requirements.

The machine used for the stub column compression test is a TONI-TECH 3000 kN compression machine shown in Figure 1. According to the standard, steel endplates should be used to transfer the load, and a layer of grout should be placed between the steel plate and the testing machine to facilitate aligning of the test specimen. As the test machine has a spherical bearing head, the grout layer wasn't needed.

![Figure 1: TONI-TECH 3000kN compression machine](image)

The specimens were geometrically aligned in the test machine. The only readings from the test were load and vertical displacement provided by the test machine. No dial gages or electrical gages were used to get more accurate strain measurements. Next, the test speed was set to 10 kN/min for the intact specimens and 8 kN/min for the damaged ones. The standard requirement is a maximum loading rate of 21 MPa/min, corresponding to about 12.8 kN/min. The test was set to stop after a 10 kN drop in loading.

3.1.2. Test of stub-columns with cracks. In addition to the two intact specimens, four stub column specimens with cracks were tested in order to investigate the effect of cracks and crack orientation relative to the load and length direction, see Figure 10. The size of the crack was 23.5% of the circumference (identical to the medium crack induced on the slender columns) and 4 mm holes were drilled at the crack tip. The first test had a crack perpendicular to the length direction of the column, as used in the column tests. The other three specimens had the crack rotated to 45° and parallel to the length direction of the stub column. The crack was placed in the centre of the length of the specimen.

Specimens were identified by: Tube diameter – thickness – diameter hole size - the extent of damage as a percentage of the circumference – angel on crack relative to end surface - chronological test number within its group. As an example, specimen 70-29-4-76.5-45-2 has a diameter of 70 mm, a thickness of 2.9 mm, hole size diameter of 4 mm, 76.5% undamaged circumference (equivalent with a crack of 23.5%), the crack is rotated 45° relative to the end surface, and number 3 of its kind.
3.1.3. Column preparation (making of the crack and the holes). The crack sizes chosen were 12%, 23.5%, and 38.5% of the circumference. These crack sizes correspond to a reduction in capacity according to NORSOK N-004 of 25%, 50%, and 75% of an intact column, respectively. Given that NORSOK N-004 provides formulae for cracked tubulars in the form of an equivalent dent, it seems to be assumed that the crack surfaces will not be in contact under compressive loading, which leads to an eccentricity in the centre of rigidity in the damaged cross-section. In addition, eccentricity is also introduced in these tests by the presence of the crack arresting holes. As a result, an additional local moment will be present in the columns.

A parameter not considered in the NORSOK standard is the placement of the crack in length-direction of the column. To obtain the minimum load bearing capacity, the crack needs to be placed where the maximum deflection occurs at buckling. For the test setup used in this experiment, the supports were fixed at the bottom and the load block at the top of the column is hinged. The location of the maximum deflection in the length direction was determined by testing an intact column until failure, which then became the basis for the crack position as shown in Figure 2. It was also decided to position the crack in parallel with the end surfaces of the tube with the intention to obtain the minimum capacity.

The simulated cracks were made with an air-powered multi-cutter attached to a lathe. This method made it possible to get thin and precise cuts, but not as thin as a real fatigue crack which would in most cases close in compression and be able to carry compressive loads. The crack’s ability to transfer compressive stresses will be dependent on the space between the crack surfaces, as shown by Paik et al [9]. In a fatigue crack this is expected to be minimal. To better replicate this behaviour, a filler material of the same pipe steel was placed in the cut, as shown in Figure 3.
The slender column specimens were identified similar to the stub-columns by Tube diameter – thickness – diameter hole size - the extent of damage as a percentage of the circumference - chronological test number within its group. Some of the specimens have an additional OD in the identification, an abbreviation for "Opposite Direction", describing the placement of the crack relative to the test machine as it was assumed that there could be an eccentricity in the test setup, as further described later.

3.1.4. Test setup (Test machine, boundary conditions). The machine used in the test was a modified TONI TECHNIK Baustoffprüfsysteme GmbH D-1000. The test setup was intended to work as a fixed–hinged supported setup, where the bottom support is working as the fixation. A detailed overview of the setup is shown in Figure 4.

![Figure 4: Top cylindrical hinge (left) and bottom fixed support (right) in test setup, respectively](image)

3.1.5. Assumptions in the test setup. The following assumptions have been made during testing:

1. The upper boundary condition is assumed hinged, and the bottom is assumed fixed. However, the supports cannot be welded to the cups or the machine and, hence, full end fixation was not achieved.
2. The effective column length is assumed be determined by a k-factor times the full pipe length, while it may be reduced with the end cups length in reality.
3. The pipe ends are flat and perpendicular to the load direction and have uniform pressure.
4. The load is acting parallel and in the centre of the tube.
5. Any misalignment will cause additional moments due to eccentricity.
6. Any effect of deformation of the end cups are ignored.
7. The effect of the test setups forcing the buckling direction around the major axis of the top cylindrical hinge, shown in Figure 4, can be ignored. Since circular hollow section stiffness is equally distributed around the neutral axis, the hinges should ideally be spherical to allow the tube to buckle in any direction.

3.1.6. Test Procedure. The test procedure used for the centrally loaded column test is according to Ziemian [10]. Before testing the variation in cross-sectional shape and area and initial out of straightness were measured on some of the specimen, showing imperfection within EN 10217-1 [11] tolerances. Hence, the imperfections were considered small enough not to have any significant influence on the test results. Further, the preload was set to 5kN to preserve alignment establishment and test speed was set to 4.2 kN/min to meet procedure requirements. As the target for these tests was to obtain the ultimate strength of the columns, the only measurements recorded were the load and overall shortening of the columns.
3.1.7. Testing. The specimens were placed in the test machine with the crack placed in the buckling plane defined by the test setup. To ensure that the end support in the test setup will not experience excessive deformations and sliding during testing, the specimens were pre-loaded until 30% of the estimated yield strength and unloaded down to approximately 5% loading. After this pre-loading, the force-deflection curve was compared to the stub column test and testing commenced if these were found to agree reasonably well.

The first specimen was an intact column used as a reference and basis for the crack placement. Next, four specimens were tested with crack sizes 12%, 23.5%, and 38.5% of the circumference, all with the crack facing the same direction. The specimen with the smallest crack (identified UP) was placed upside down in the test machine and was re-done. Further, three specimens with the same set of crack sizes were tested with the crack facing the opposite direction (identified OD). Finally, the last three specimens with crack size 23.5% of the circumference and different hole sizes were tested.

3.2. Result of experimental work

3.2.1. Stub column results. Stub column tests were used to get the material properties by compressing short, intact columns until failure. The yield strength was found to be 370 MPa by using the standard 0.2% strain offset method. The engineering stress strain curve corresponding to the stub column tests is shown in Figure 5.

![Stress strain curve, stub column test](image_url)

Figure 5: Stress strain curve, stub column test

An estimate of the specimen's Young's modulus was found to be 150 GPa from the stress-strain curve by dividing $\Delta \sigma$ by $\Delta \varepsilon$ in region 150-250 MPa. The reason for choosing this region is the test settle at the beginning and the effect of residual stresses when the loading is getting larger. For more accurate determination of Young's modulus, better displacement measurements are needed. The maximum load is shown in Table 1

| Reference number | Specimen Length (mm) | Outer Diameter (mm) | Thickness (mm) | Maximum loading (kN) |
|------------------|----------------------|---------------------|----------------|----------------------|
| S1               | 234                  | 70                  | 2.9            | 235.15               |
| S2               | 234                  | 70                  | 2.9            | 239.91               |
3.2.2. Column test results. The protocol below is an overview of all the column results. Figure 6 shows the max loading (failure load) of each specimen and the load-displacement curve of each specimen.

![Figure 6: Load-displacement curve and max loading for each test specimen](image)

The specimen identified UD was un-intentionally placed upside down in the test machine and, hence, the crack was erroneously placed further up than intended. As a result, the test was redone with a new specimen. These four first specimens all had the crack facing the same direction relative to the test machine and all the specimens buckled in the same direction, resulting in the cracks closing as shown in Figure 7. The erroneously placed specimen showed a higher capacity than the correct one, which confirms good placement of the crack. Hence, the test was decided to be included.

![Figure 7: Deformed shape of the cracked area for test 3, 4 and 5 (crack of 12%, 23.5%, and 38.5% of the circumference respectively)](image)

As the first five specimens (including the intact specimen) buckled in the same direction relative to the test machine, it was assumed that there could be an eccentricity in the test setup. To verify this, it
was decided to test three more specimens with the same crack sizes and rotate the specimen 180° relative to the testing machine. As expected, the buckling still happened in the same direction relative to the test machine, now opening the cracks. The resulting eccentricity observed from these experiments are further discussed in Riise [2].

Figure 8: Deformed shape of the cracked area for specimen 6, 7 and 8 (crack of 12%, 23.5%, and 38.5% of the circumference respectively)

The last three specimens were prepared with larger diameter holes, 6, 8 and 10 mm respectively, but still maintaining a crack length of 23.5% of the circumference. The specimens were placed in a position where crack opening is expected. The first specimen buckled in the same direction as all the other specimens, but the last two specimens (8 and 10mm holes respectively) buckled the opposite direction and the crack closed. A summary of the results from the tests are provided in Table 2.

Figure 9: Deformed shape of the cracked area for specimen 9, 10 and 11 (6, 8 and 10mm hole respectively)
### Table 2: Test results for specimens

| Reference number | Specimen length (mm) | Outer Diam (mm) | Thickness (mm) | Hole size diam (mm) | Crack size | Placement of specimen | Maximum loading (kN) |
|------------------|----------------------|-----------------|---------------|---------------------|------------|-----------------------|----------------------|
| 1                | 1500                 | 70              | 2.9           | -                   | No crack   | -                     | 208.95               |
| 2 (UP)           | 1500                 | 70              | 2.9           | 4                   | 12%        | 0°                    | 203.75               |
| 3                | 1500                 | 70              | 2.9           | 4                   | 12%        | 0°                    | 200.61               |
| 4                | 1500                 | 70              | 2.9           | 4                   | 23.5%      | 0°                    | 204.22               |
| 5                | 1500                 | 70              | 2.9           | 4                   | 38.5%      | 0°                    | 210.70               |
| 6                | 1500                 | 70              | 2.9           | 4                   | 12%        | 180° (OD)             | 206.49               |
| 7                | 1500                 | 70              | 2.9           | 4                   | 23.5%      | 180° (OD)             | 199.30               |
| 8                | 1500                 | 70              | 2.9           | 4                   | 38.5%      | 180° (OD)             | 200.67               |
| 9                | 1500                 | 70              | 2.9           | 6                   | 23.5%      | 180° (OD)             | 210.54               |
| 10               | 1500                 | 70              | 2.9           | 8                   | 23.5%      | 180° (OD)             | 202.37               |
| 11               | 1500                 | 70              | 2.9           | 10                  | 23.5%      | 180° (OD)             | 195.20               |

1. The specimen identified UP was placed upside down in the test machine.
2. Specimens marked with OD were rotate 180° (about z-axis) relative to the testing machine.
3. All cracks were placed parallel with end surface and 705 mm from the bottom support.

### 3.2.3. Cracked stub column test Results

All the slender column tests reported showed an insignificant capacity reduction, in contrast to the formulae by NORSOK N-004. To further study the effect of cracks in tubular members, angled cracks in stub columns were introduced. The total stub column tests are shown in Table 3 and the deformed shape of these shown in Figure 10, including the specimens with no crack previously reported. The 0° is included as a reference with identical crack to the full column tests.

### Table 3: Stub column tests results

| Reference number | Specimen Length (mm) | Outer Diam (mm) | Thickness (mm) | Hole size diam. (mm) | Crack size | Angle (°) | Maximum loading (kN) |
|------------------|----------------------|-----------------|---------------|---------------------|------------|-----------|----------------------|
| S1               | 234                  | 70              | 2.9           | -                   | No crack   | -         | 235.15               |
| S2               | 234                  | 70              | 2.9           | -                   | No crack   | -         | 239.91               |
| S3               | 234                  | 70              | 2.9           | 4                   | 23.5%      | 0°        | 235.42               |
| S4               | 234                  | 70              | 2.9           | 4                   | 23.5%      | 45°       | 203.70               |
| S5               | 234                  | 70              | 2.9           | 4                   | 23.5%      | 45°       | 202.32               |
| S6               | 234                  | 70              | 2.9           | 4                   | 23.5%      | 90°       | 228.80               |
3.3. Discussion on the experimental work

3.3.1. Discussion stub-column test
The stub column tests showed a mean yield strength of 370 MPa which is considerably larger than the (characteristic) nominal yield strength of the 235 MPa virgin material (P235TR1). This can be explained by the strain hardening and ageing of the steel as a result of the plastic deformation of the steel under the cold forming possess.

As the results in Table 3 show, the 45° rotated crack gives a considerable reduction in capacity. The bearing effect on the crack surface is no longer present, and the deformed shape indicates a significant amount of torsion present in the specimen. The specimen with a 90° crack showed a relatively small reduction.

3.3.2. Discussion of column test results
In essence, the introduction of cracks and crack arresting holes did not change the capacity of the columns significantly, as the crack surfaces are in contact and are transferring stresses under
compression up to reaching the ultimate capacity. A certain trend in the capacity seems to be a result of the size and placement of the crack arresting holes. The size and presence of the cracks seems to have negligible effect on the compressive capacity.

Test 3-5 indicated a slight increase in capacity with increasing crack size. This is believed to be a result of the crack arresting holes getting closer to the neutral axis. For the specimens 6-8, the eccentricity due to holes should be working against the assumed eccentricity in the test setup, and the expected capacity should be higher than in for specimen 3-5. However, the variations observed in these tests are in order of the expected randomness from such tests, and a significant trend cannot be seen for all the specimens.

4. Numerical model
The tested cracked tubular columns were further analysed by a non-linear finite element analysis, in order to calibrate a model to make this type of analysis valid for other cases. A non-linear problem can be described by different types of non-linearities. In this paper, the following types of non-linearities are included:
- Material non-linearity: The stress-strain relation is non-linear.
- Geometric non-linearity: The element is exposed to a large load and large deformations change the geometry.

Four numerical models were created in Abaqus, and the procedure for performing the finite element analysis is based on the recommendations given in DNVGL-RP-C208 [12]. Properties from the experimental work was implemented in the numerical models, including material geometry, elastic and plastic stress-strain relationship and axial compression load. Three analyses were performed for all four models, one to fit the boundary conditions in the experimental test machine, the other two to match the physical buckling shape.

The numerical model includes the crack arresting holes but did not include the cracks themselves. It was evident from the experimental work that the crack surfaces were bearing on each other allowing stress transfer from one side of the crack to the other as long as the crack were under compression.

The crack lost ability to transfer stresses, or opened, after reaching the ultimate stress. However, since the post-buckling behaviour is not of primary interest in this study, the chosen simplification was seen adequate.

4.1. Geometric model
The geometric properties for all four numerical models are listed in Table 4.

| Sample     | Diam (mm) | Length (mm) | Thickness (mm) | Crack size | Hole size (mm) |
|------------|-----------|-------------|----------------|------------|----------------|
| 70-2.9-4-100 | 70       | 1500       | 2.9            | -          | -              |
| 70-2.9-4-88  | 70       | 1500       | 2.9            | 12%        | 4              |
| 70-2.9-4-76.5 | 70      | 1500       | 2.9            | 23.5%      | 4              |
| 70-2.9-4-61.5 | 70      | 1500       | 2.9            | 38.5%      | 4              |

4.2. Boundary conditions
Two reference nodes were created in the middle of each end of the column. These reference nodes were tied to all nodes at the column ends to simulate the rigid endplates with controlled degrees of freedom. Three different sets of boundary conditions are used in the numerical models:
- Case 1: bottom reference node is fixed, and the top reference node is hinged.
- Case 2: bottom reference node is fixed, and the top reference node is fixed.
- Case 3: bottom reference node is hinged, and the top reference node is hinged.

The load is applied to the top of the columns. Figure 12 shows the buckling modes for the three different sets of boundary conditions.
Figure 12: Boundary conditions: a) fixed-hinged, b) fixed-fixed, c) hinged-hinged.

4.3. Element type
The steel columns were modelled by 4-node general-purpose shell elements that uses reduced integration with hourglass control (Abaqus S4R shell element), which is capable of handling large strains and rotations.

4.4. Material model
The material model is described by:
1. Yield surface according to von Mises yield criteria.
2. Isotropic hardening where the yield surface location is the same but the size of the surface increases.
3. Plastic flow rule defining the change of the inelastic deformation.
   The yield strength used in the material model is taken as the mean yield stress from the stub-column specimens (370 MPa) and the mean value of the ultimate tensile strength is 404 MPa.

4.5. Initial geometric imperfections
The geometric imperfection presented in the numerical model is an artificial imperfection that represents the combined effect from residual stresses, welding stresses, initial bow, sections and thickness variations assumed to be present in the real column.
   The geometric imperfection is defined as out-of-straightness in the column, where the shape is taken as same shape of the global buckling mode with a scaling factor calibrated to provide the same load carrying capacity as per the reference column. An imperfection scale factor equal to the column length divided by 1000 were applied to the global buckling mode.

4.6. Analysis methodology
Based on the methodology provided in DNVGL-RP-C208 [12], the following steps have been used for the non-linear finite element analysis:
1. Preparation of the numerical model: considering material model, actual geometry, boundary conditions, loading, mesh configuration, etc.
2. Determine relevant buckling modes by performing a linear eigenvalue analysis on the perfect column to determine the relevant buckling mode and the appropriate critical load.
3. Calibration of the geometric imperfection against the experimental work to determine the imperfection shape and scale factor.
4. Performing a non-linear buckling analysis on the imperfect column to obtain the axial capacity.
4.7. Results of the numerical model

The results from the FEA are compared with the results from the experimental work performed by Riise [2] and hand calculations performed using NORSOK N-004 as shown in Table 5. The load-displacement curves for the experimental tests and the FEA for the intact case and the 12.0% crack case is shown in Figure 13.

The results as shown in Table 5 indicates a reasonable match between the experimental and the numerical capacities. Some deviation is seen in the two rouge experiments as discussed earlier and the 70-2.9-4-88-2 specimen. The comparison between the NORSOK N-004 capacity and the experimental work shows a reasonable match for the reference model, but for the cracked specimens NORSOK N-004 gives more conservative capacities with increasing crack size. The calculations according to NORSOK N-004 [4] can be found in Vågen [1].

Two representative sets of load-displacement curves are shown in Figure 13, indicating that the FEA results does not perfectly match the experimental measured values. It should be noted that the experimental data is shifted 0.6 mm to the left to correct for assumed displacement in the supports. With this adjustment the pre-buckling behaviour seems to fit reasonably. However, the post-buckling behaviour differs quite significantly, as the behaviour in this phase will be significantly influenced by the presence of the crack. Nevertheless, this is not the main area of interest in this paper.

| Sample | Crack size\(^1\) | \(P_{\text{NORSOK}}(k=0.7)\) | \(P_{\text{Exp}}\) | \(P_{\text{FE,ref}}^*\) |
|--------|------------------|------------------|------------------|------------------|
| 70-2.9-4-100 | 0 | 181.27 | 208.95 | 208.5 |
| 70-2.9-4-88-2 | 12.0 | 168.77 | 200.61 | 205.2 |
| 70-2.9-4-88-3-OD\(^3\) | 12.0 | 168.77 | 206.49 | 204.9 |
| 70-2.9-4-76.5-1 | 23.5 | 138.55 | 204.22 | 205.1 |
| 70-2.9-4-76.5-2-OD\(^3\) | 23.5 | 138.55 | 199.30* | 209.9 |
| 70-2.9-4-61.5-1 | 38.5 | 88.61 | 210.70 | 210.0 |
| 70-2.9-4-61.5-2-OD\(^3\) | 38.5 | 88.61 | 200.67* | 203.1 |

1. Crack size is given in percent of the original circumference,
2. UD = sample was put wrong way in the test machine,
3. OD = the sample was rotated 180° around z-axis,
4. FE,ref = fixed-hinged finite element model,
* There is a possible error in the experimental work, as the load-displacement curve for these samples (Figure 7) indicates a somewhat strange behavior during the testing.
5. Conclusion
This paper presents experimental and numerical evaluation of the axial capacity of tubular members with simulated cracks and crack arresting holes under pure compressive load. The simulated cracks are assumed to represent a real crack in that it can transfer compressive stresses but are unable to transfer tensile stresses. If the crack surfaces of a real crack are deteriorated to the extent that they are not able to transfer compressive stresses, these tests will not be applicable.

There is, to the knowledge of the authors, no previous experimental research on the axial capacity of cracked tubular members. Hence, experimental tests were needed to better understand the effect of fatigue cracks on the capacity of tubular members and to validate the formulae in the now superseded edition of NORSOK N-004 [4], indicating that cracks in tubular columns would significantly reduce axial compressive capacity.

The experimental tests indicates that cracks perpendicular to the direction of loading do not have a significant impact on the compressive capacity of a tubular columns, contrary to the formulae in NORSOK N-004 [4]. However, the presence of crack arresting holes seems to have a slight impact on the compressive capacity. Finite element analysis was performed and provided similar results to the experimental tests.

To further study the effect of cracks in tubular members, angled cracks to the direction of loading in stub columns were introduced. The test results showed a significant reduction in the axial capacity for the 45° crack due to torsion and sliding of the crack surface. This indicates that angled cracks are having a larger impact on the axial capacity of a tubular member than straight cracks.

The conclusion to be drawn from these experimental and numerical tests could be that a crack perfectly perpendicular to the load direction in a tubular column would not reduce the capacity significantly, but an angled crack and the presence of crack arresting holes would reduce the capacity.

6. Further work
Although these idealistic experiments are only considering pure compression and only one slenderness ratio, the results are believed to contribute to better insight on axial compression capacity of cracked tubular members.

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**Figure 13:** Load-displacement curves for experimental tests and FEA analysis for intact case and 12% crack case
Further work to study angled cracks in full size columns, different slenderness ratios and combined loading (compression, shear and bending) is needed to fully understand the capacity of cracked tubular columns. In addition, cracks at various locations along the length of the columns should be investigated. Furthermore, naturally induced cracks should be investigated to better understand how cracks affect the capacity.

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