# TOWARDS ECONOMIC DESIGN OF A PRESSURE VESSEL MADE OF DUPLEX STAINLESS STEEL

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**ABSTRACT**

Pressure vessels have been used for a long time in various applications in oil, chemical, nuclear and power industries. Although high strength steels have been available in the last three decades, there are still are some provisions in design codes that preclude a full exploitation of its properties. This was recognized by the European Equipment Industry and an initiative to improve economy and safe use of High Strength Steels in the pressure vessel design was expressed in the evaluation report [1].
Duplex Stainless Steel (DSS) has a mixed structure which consists of ferrite and austenite stainless steels, with austenite between 40% and 60%. The current version of the European standard for unfired pressure vessels EN 13445:2002 contains an innovative design procedure based on Finite Element Analysis (FEA), called Design by Analysis-Direct Route (DBA-DR). According to the code duplex steels should be designed as they belong to ferritic stainless steels. Such statement seems to penalize the DSS grades for the use in unfired pressure vessels [2].
The aim of this paper is to present recent results from LTU obtained within the ECOPRESS project (2000-2003) [3] indicating possibilities towards economic design of pressure vessels made of the EN 1.4462 designation according to European standard [4].

**KEYWORDS**

Duplex stainless steel, pressure vessel, Finite Element Analysis, uniaxial test, membrane test, welded nozzle test

## INTRODUCTION

The use of stainless steel is rather wide. It spans from non-structural applications, such as kitchen sinks, to demanding structural applications for example in bridges, as one 62m long pedestrian bridge made of the Duplex 2205 over Sickla channel in Sweden. Duplex 2205 is the commercial name of the steel grade EN 1.4462, [4]. It is also used for a railway carriage construction and for structural components that may be exposed to corrosion or are difficult to inspect. There are also some advantages of stainless steel in comparison to carbon steel at elevated temperatures, better retention of strength and stiffness, especially at temperatures higher than 500$^{o}$C. Generally, stainless steel is used in structures because of its corrosion resistance but also for its mechanical properties.

One of the basic concerns in the European Equipment Industry stated in the evaluation report [1] was economic and safe use of High Strength Steels in pressure vessel design. Process corrosivity and need for wall thickness reduction of oxonation reactors, which were firstly made of austenitic stainless steels, led to a design using the high strength stainless steel so called "duplex" material. Duplex Stainless Steel (DSS) has a mixed structure which consists of ferrite and austenite. The combination is developed to offer more strength than either of those stainless steels. However, it is believed that the economic use of DSS is restricted by over-conservative design strength which is governed by the provisions for ferritic material [2].
The current version of the European standard for unfired pressure vessels EN 13445:2002 contains an innovative design procedure based on Finite Element Analysis (FEA), called Design by Analysis

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(DBA) direct route. It is given in the normative Annex B where the design strength depends on the crystallographic texture of the steel grade.
For ferritic grades, the design strength $f$ is governed by the yield strength or proof stress at 0.2% effective plastic strain and at calculation temperature $t$, $R_{p0.2/t}$ with the material safety factor depending on the ratio $\frac{R_{p0,2/t}}{R_{m/20}}$, for $\frac{R_{p0,2/t}}{R_{m/20}} \leq 0.8$ $\gamma_R = 1.25$.
For austenic grades with maximum elongation of $30\% \leq A_5 < 35\%$ the design strength is the proof stress at plastic strain of 1.0% $R_{p1.0/t}$ divided by the same safety factor $\gamma_R = 1.25$.
Duplex is a grade of stainless steels with a balanced two-phase structure with austenite between 40% and 60%, but according to the code it should be designed as it belongs to ferritic stainless steels. These statements seem to penalize the DSS grades for the use in unfired pressure vessels.
Results presented in the paper were obtained at LTU within the research project ECOPRESS [3]. One of the objectives in the project was to work out conditions to remove unnecessary conservatism by applying advanced methods for the full exploitation of properties of the new steels.

## 1. CHEMICAL COMPOSITION AND MATERIAL CHARACTERISTICS

At the time when stainless steel was developed, about 80-years ago, the use was limited to very few applications, since those grades were not possible to form neither to weld. Grades suitable for welding and forming were introduced in the 1950s, in forms of nitrogen alloyed austenitic stainless steels. Research in this field was quite large and in late 1970s the elevated nitrogen avenue including ferritic-austenitic stainless steel, commonly known as duplex, was introduced on the market. The duplex stainless steel of today combines the best performance of ferrite and austenite.

Stainless steels are steel alloys containing Chromium, which makes the steel resistant against corrosion. The definition of a stainless steel is that the Chromium content should be at least 10.5 %. Chromium and Nickel are the main alloying elements in stainless steel. Then there are several other alloying elements, like Molybdenum, Manganese, Nitrogen and Sulphur [5]. A great number of different grades with widely varying composition are standardised in USA and Europe. A broader overview, is given in Table 1 where a composition range is shown for six categories. The names of the first five refer to the dominant components of the microstructure in the different steels. The name of the last group refers to the fact that these steels are hardened by a special mechanism involving the formation of precipitates within the microstructure.

**Table 1**. Chemical composition ranges for different stainless steel categories acc. to [5]

| | C [%] | Cr [%] | Ni [%] | Mo [%] | Others |
|---|---|---|---|---|---|
| Martensitic | >0.10<br>>0.17 | 11-14<br>16-18 | 0-1<br>0-2 | -<br>0-2 | V |
| Martensitic-austenitic | <0.10 | 12-18 | 4-6 | 1-2 | |
| Ferritic | <0.08<br><0.25 | 12-19<br>24-28 | 0-5<br>- | <5<br>- | Ti |
| Ferritic-austenitic (duplex) | <0.05 | 18-27 | 4-7 | 1-4 | N,W |
| Austenitic | <0.08 | 16-30 | 8-35 | 0-7 | N,Cu,Ti,Nb |
| Precipitation hardening | | 15-17<br>12-17 | 7-8<br>4-8 | 0-2<br>0-2 | Al,Cu,Ti,Nb |

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The duplex stainless steels contain several grades, which range in strength and corrosion performance depending on their alloy content. The chemical composition of Duplex 2205(EN 1.4462) is listed in Table 2 [6 ].

**Table 2** A typical chemical composition of Duplex 2205, [%].

| Grade | C | N | Mo | Cr | Ni |
|---|---|---|---|---|---|
| EN 1.4462 | 0.02 | 0.17 | 3.1 | 22 | 5.7 |

There are many mechanisms that make the high strength performance possible. Solid solution hardening occurs in duplex to different degrees. In different phases during the thermo-mechanical history, internal stresses develop and a strengthening effect arises. It is the balance of austenite/ferrite that mainly controls the mechanical properties.

## 2. UNIAXIAL TESTS

Standardised coupon tests were carried out in order to obtain the engineering stress-strain relation for Duplex 2205. The anisotropic performance is very clear when comparing the tests performed transverse and along the rolling direction.

The anisotropy appears in different directions due to the elongated lamella structure. A special duplex texture tends to develop in the material. It is known that the anisotropy effect is more emphasised in thinner rolled plates. Results obtained on 4mm thick specimen are shown in Fig.1 to illustrate the anisotropy effect. The specimen (ref_test_T) was taken from the direction transverse the rolling direction and the specimen (ref_test_L) was along the rolling direction, Fig.1.

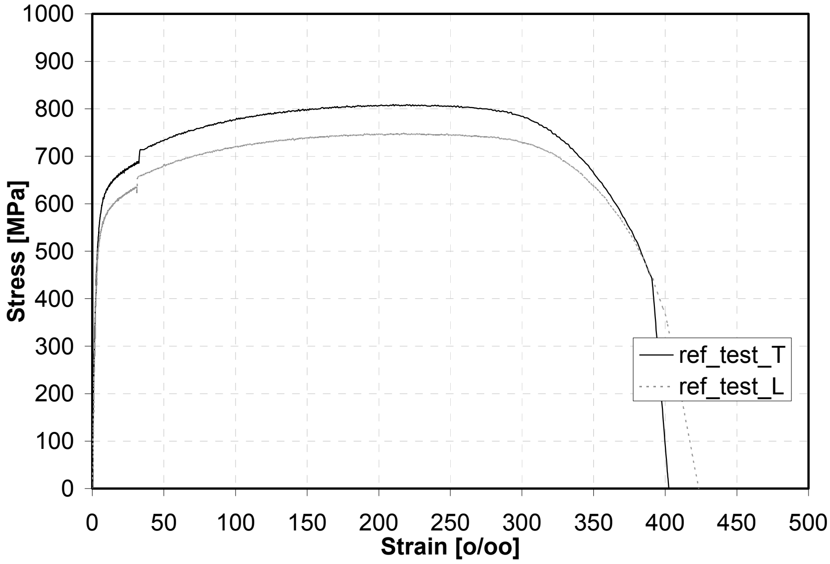


**Fig. 1** *Comparison of stress-strain relation between coupon tests along and transverse the rolling direction.*

For duplex materials there are several welding methods that are feasible. Normally the yield and tensile strength of the weld metal are the same or higher than of the base material. However, the elongation at the failure is lower than for the base material.

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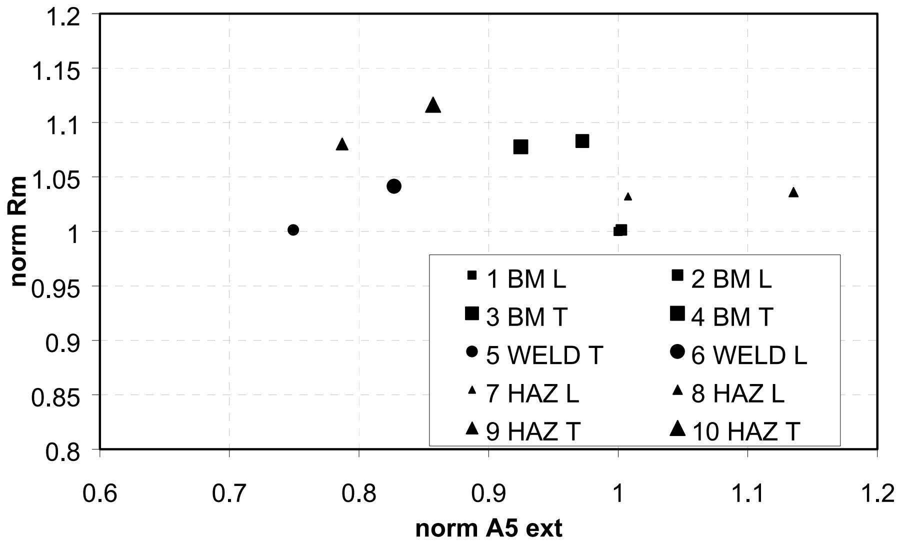


**Fig. 2** *Normalized results from uniaxial test of weld and HAZ.*

In Fig. 2 the uniaxial tests of the weld metal and HAZ are normalized with test 1 BM L (ref_test_L). Test 1 BM L was used as a reference test with values of 747 MPa for $R_m$ and 39.9 % for the $A_{5\ ext}$. The symbol BM represents the base material and L or T indicates the direction, either it is along or transverse the rolling direction. The HAZ material has a rather big variation between the rolling directions in terms of $R_m$ and $A_{5\ ext}$. For the HAZ transverse the rolling direction, the strain at failure decreased compared to the base material. The weld metal has smaller elongation at the failure than the base material independent of the direction. Complete results from each uniaxial test are shown in [7].

## 3. MEMBRANE TESTS AND FE EVALUATION

A non-standardised test set-up was designed at LTU, the lay-out is shown in Fig.3. Three plain specimens, six but welded specimens and three specimens with the welded nozzle were tested to investigate the strength of the specimens in a bi-axial stress state. The out of plane displacement of the specimen (bulge) and oil pressure was measured during the tests. The load was applied with an oil pressure at a constant rate of 0.5 bar per second. The bulge was measured by a LVDT at the centre of the specimen and the oil pressure was measured in the oil pump. The strain was measured by XY-strain gauges glued on outer side of the specimen. They were in operation up to 6%, but definitely not until the failure. Therefore, FEA was used to estimate the strain level at the failure.

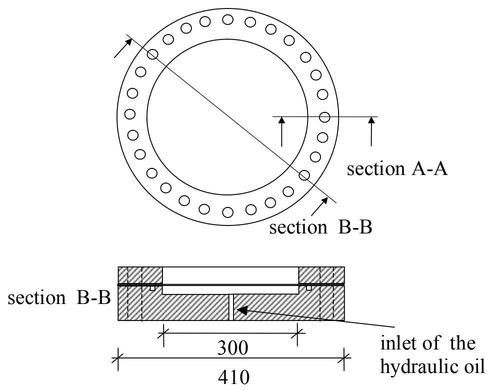


**Fig.3** *The membrane test set-up, the plate thickness was 4mm for all type of specimens*

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**Table 3** Summary of the experimental results

| Specimen type | Specimen | Internal pressure at failure [MPa] | Bulge at failure [mm] | Direction of failure | Distance from crack to centre line [mm] |
|---|---|---|---|---|---|
| Plain plate | mem1p | 39.3 | 81.4 | A | 5 |
| | mem2p | 39.7 | 79.4 | A | 6 |
| | mem3p | 39.8 | 79.8 | A | 17 |
| Butt welded plate | mem4w | 41.4 | 72.0 | A | 9 |
| | mem5w | 39.0 | 66.2 | A | 5 |
| | mem6w | 40.4 | 70.6 | A | 5 |
| | mem10w | 36.9 | 62.4 | A | 6 |
| | mem11w | 41.7 | 74.0 | P | 35 |
| | mem12w | 41.1 | 75.1 | A | 24 |
| Plate with nozzle | mem7noz | 29.1 | 45.2 | A | W |
| | mem8noz | 31.2 | 46.9 | A | W |
| | mem9noz | 30.4 | 45.8 | P | W |

Symbols:
A = crack along the roller direction
P = crack perpendicular to the rolling direction.
W = crack located at the fillet weld

Characteristic bulge-pressure results of the base material (memp), the butt-welded specimen (memw) and the specimen with the nozzle (memnoz) are shown in Fig.4. All three specimens prove to have the same stiffness almost up to 20mm of bulge. Note that the butt-welded specimens had higher resistance but the failure occurred at lower bulge. This tendency was even more emphasised for the specimens with the nozzle.

The welded nozzle test specimen were designed to investigate the affect from welded details on membranes, the nozzle itself was designed to resist the high pressure. The welding resulted in residual stresses and warped specimens. The ultimate resistance of specimens with the nozzle was highly influenced by the quality of the welds in the connection between the nozzle and the sheet. The welded detail was exposed to the largest strains and therefore the weld quality, influenced also by a welding procedure used, is the determining factor for the resistance and ductility.

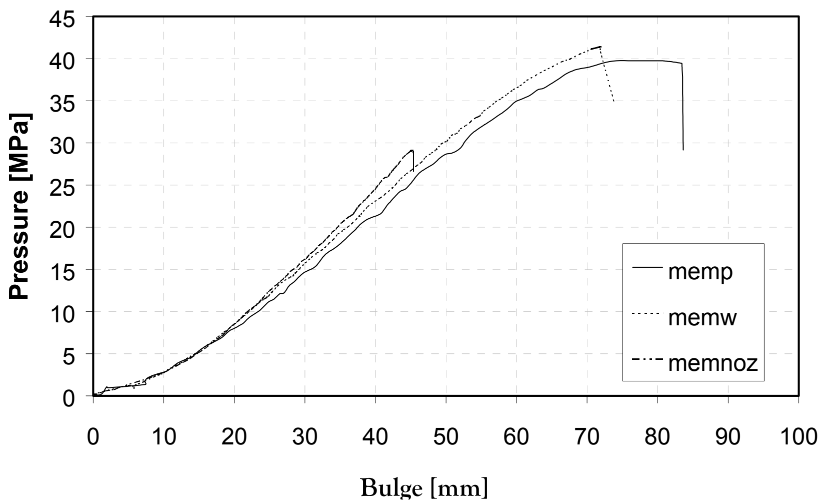


**Fig. 4** *Comparison between results of three characteristic specimens.*

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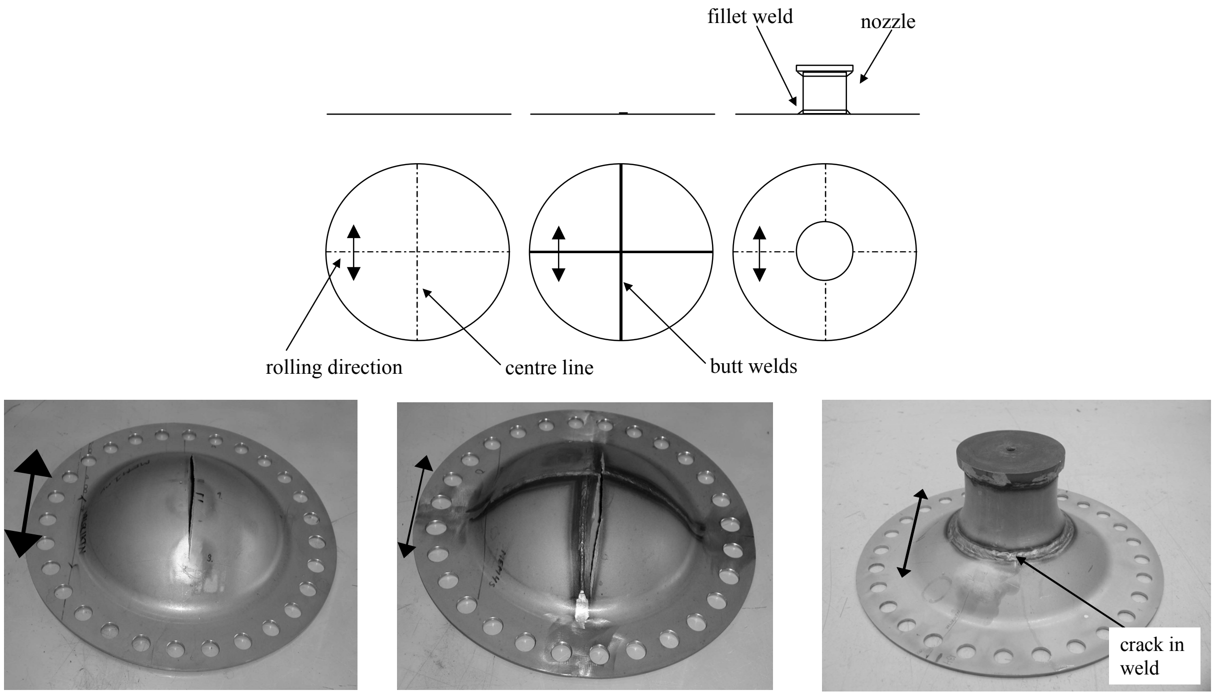
The failure mode and crack orientation are almost identical for plain and butt welded specimens. The crack propagates along the rolling direction. When studying the crack surface of the specimens with the nozzle some spots of possible slag were found, which certainly could have influenced the strength of the weld.




*a/ Plain plate* *b/ Butt welded plate* *c/ Plate with nozzle*

**Fig. 5** *Specimens after testing, the arrow indicates the rolling direction.*

The scattering of the test results, failure load and corresponding bulge, for all 12 tests is shown in Fig.6. The test results are normalized using mem1p as a reference test where the failure load was 39.3 MPa and the corresponding bulge 81.4 mm. It is obvious that the plain specimen have very small scattering. Welded test specimen, especially tests with butt welds show greater variation between results. That is due to imperfections in the weld metal.

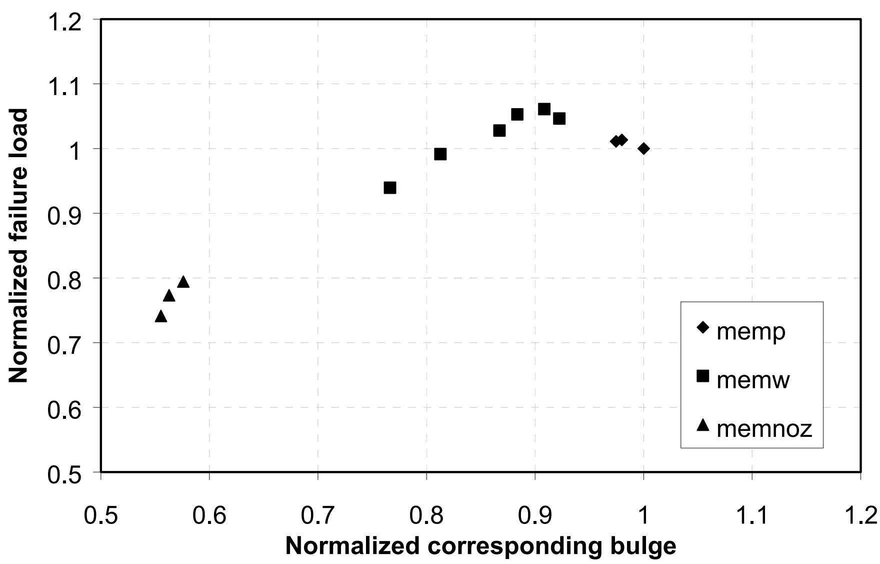



**Fig. 6** *Summary of membrane test results, maximum load vs. maximum bulge with test specimen mem1p as reference specimen.*

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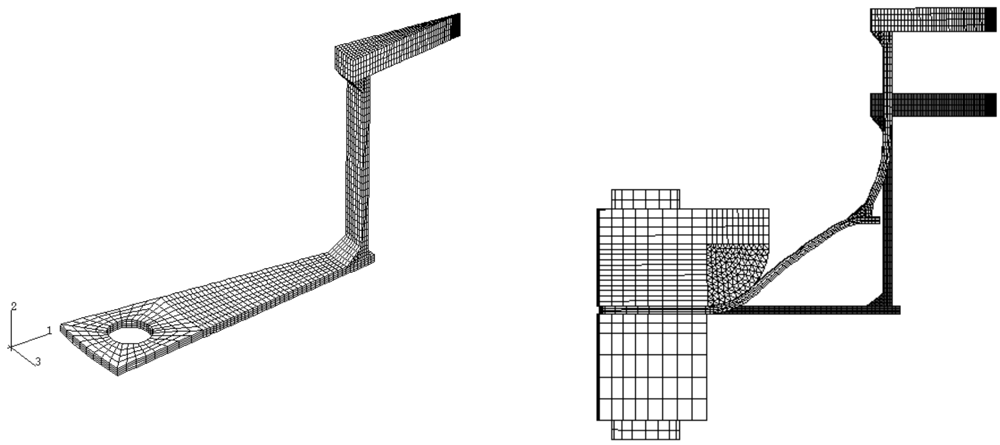
A rather complex 3D FE model was necessary in order to model the behaviour of the membrane specimens: the plain specimen and specimen with the nozzle. ABAQUS, a commercially available FE code, was used to model non-linear problem involving elasto-plastic hardening constitutive model, contact problem and large deformations. Six-node and eight-node solid elements were used to model specimens and a part of the test set-up. Since the geometry of the test equipment and the expected deformations were symmetric, only a 28$^{th}$ of the set-up was modelled, see Fig.7. A local coordinate system was used, the cylindrical coordinates at the boundaries, to insure the proper definition of the boundary conditions.
The model consists of four different bodies that do not have any common nodes, the ring, the rig, the bolt and the specimens. These four bodies interaction were modelled in the ABAQUS using contact surfaces. The friction coefficient was defined for all contact surfaces. Between the bolt head and the ring/rig the contact problem was defined using a kinematic constrain. An equation that ties one node from one body together with one node from the other body was specified. The equation option defines relative displacement between two nodes. In this case these two nodes had the same displacement along the bolt axis. This option was necessary in order to introduce the tightening force in the bolt and to take into account the friction force appearing between the specimen and the test set-up. The bolts were tightened to approximately 50 % of their ultimate strength in the experiments. This was necessary in order to mobilise the required contact force and to hold the specimen in the test set-up. To create this tightening force in the model, the axial stress of 600 MPa was applied initially in the bolt, which imposed the friction between the specimen and the test set-up.



*a/ FE mesh of the specimen with nozzle*

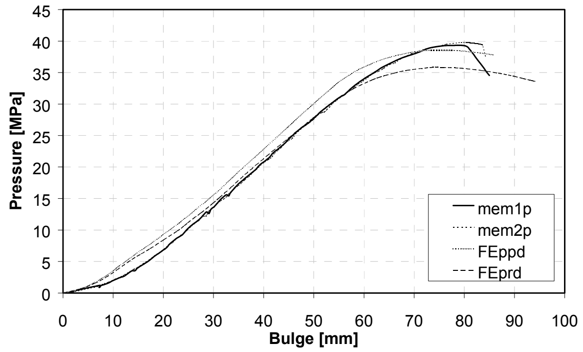
*b/ Displacement at the maximum load*

**Fig. 7** *Finite element model of 1/28$^{th}$ part of the nozzle specimen*

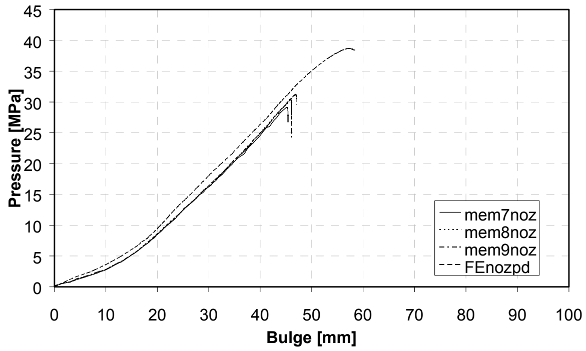
The material parameters used in the ABAQUS were derived from the coupon tests. Young's modulus was 200 MPa and Poisson's ratio was 0.3. The true stress and true plastic strain were used to describe isotropic hardening. This means that the yield surface changed size uniformly in all directions, such that the yield stress increases in all directions as plastic straining occurs.
The analysis was performed using implicit code and the Riks method was used as the numerical solver.

A very good agreement between the measured bulge and bulge predicted by FE calculations was obtained for both specimen types, the plain and the nozzle specimen. In all computations the unloading was obtained which clearly defined the maximum load. The agreement of the initial

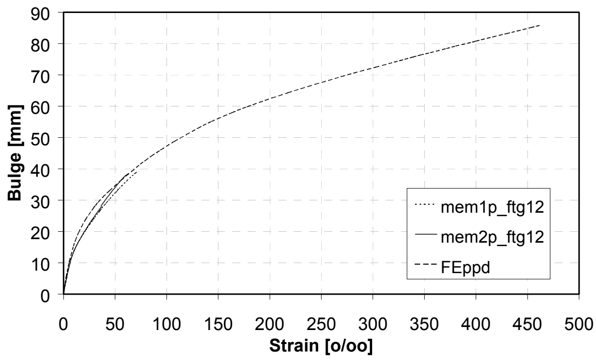
stiffness, the maximum load and the ductility shown in Fig 8.a indicates that very reliable FE model was used. Figures 8.c and 8.d show very good agreement of the measured strain, the resultant strain, with the computed strain. The resultant strain is the vector sum of two in plane strain components, either measured or computed in FE analysis.
The FE model was created to study only the main test features, the bulge and the maximum load, with no ambition to introduce any material imperfections due to welding. This is the reason for the higher ultimate load prediction than it was the failure load obtained in the experiments on the nozzle specimen, Fig.8.b.



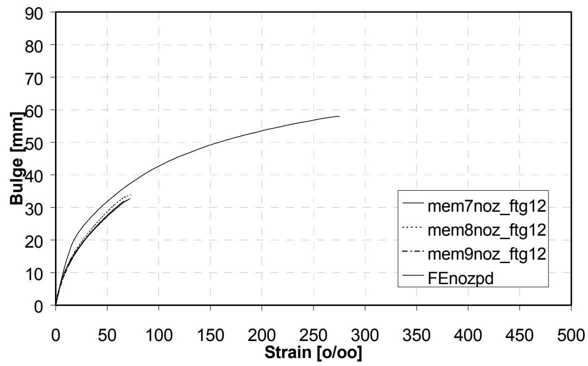

*a/ The global behaviour of plain specimens*




*b/ The global behaviour of nozzle specimens*




*c/ Measured and calculated resultant strains of plain specimens*




*d/ Measured and calculated resultant strains of nozzle specimens*

**Fig.8** *Comparison of experimental results and FE calculation*

## 4. DESIGN BY ANALYSIS- DIRECT ROUTE, acc. TO ANNEX B [8]

Finite Element Method is widely used for computation of pressure vessels for cases not covered by Design by Formula (DBF) route or as a complement when detailed investigation is required. There are two possibilities available for Design by Analysis (DBA): direct route (DR) and stress categorization route (SCR). The stress categorization route is derived for assessing results from linear thin-walled shell theory which requires categorization of stresses, or part of stresses, into primary, secondary and peak stresses. This method is used in many national standards despite of problems associated with categorization, non-uniqueness of determination of primary stresses.

The direct route is based on non-linear analysis and deals more clearly with failure modes than stress categorization route and the results give better insight into behaviour of the structure and provides possibilities for improvement.
In the normative annex of EN 13445-3, Annex B, design checks for five failure modes are included:

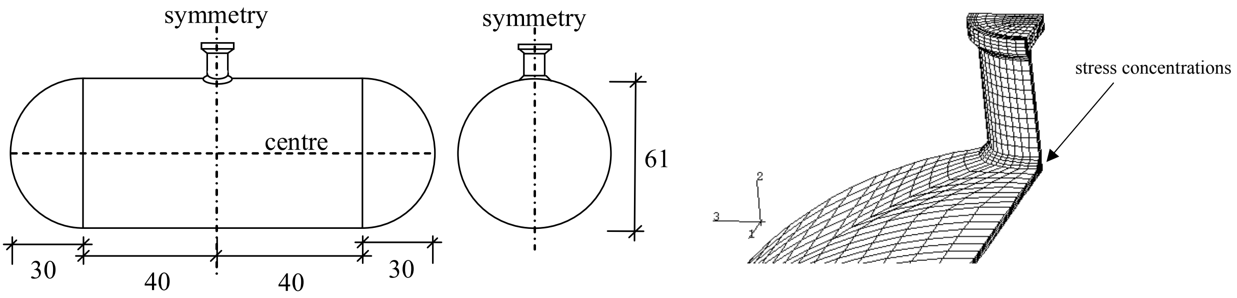
- gross plastic deformation (GPD), with corresponding failure mode of ductile rupture and excessive local strains
- progressive plastic deformation (PD) design checks
- instability (I) design checks
- fatigue (F) design checks
- static equilibrium (SE) design checks

According to Annex B, the design resistance shall be determined using the FE model with:

- linear elastic ideal-plastic constitutive law
- first order theory
- Tresca’s yield criterion and associate flow rule or if von Mises’ criterion is used than the design stress shall be decreased by the multiplication factor $\frac{\sqrt{3}}{2}$
- partial safety factor for the ferritic steel
- maximum value of the principal strains has to be less than 5%

## 5. FEA OF A SIMPLE PRESSURE VESSEL

Principles of GPD design check were examined on the simple pressure vessel designed with EN 1.4462, loaded by the internal pressure at room temperature. Dimensions of the pressure vessel are shown in Fig 9.a. The thickness, of the cylinder and the nozzle, was 4mm. Only a one fourth of the pressure vessel was modelled due to symmetry.




*a/ Geometry of the pressure vessel, dimensions are in cm.*

*b/ Detail of the FE model showing the cylinder nozzle intersection.*

**Fig. 9** *The simple pressure vessel modelled by solid elements*

The same numerical procedure and the similar FE mesh were used in this model as it was used in the evaluation of the experiments. Two constitutive models, the elasto-plastic and the isotropic hardening model, were utilised to quantify an importance of the chosen constitutive model. The failure occurred at the intersection of the nozzle and the cylinder for both models. Comparison of the results are shown in Fig. 10 using the pressure versus the maximum principal strain relation. FE_lep and FE_epih are curves obtained for the elasto-plastic model and the isotropic hardening model, respectively.  The maximum load was obtained in both computations showing a rather big difference, approximately 25 higher load was obtained in the model using the isotropic hardening material model. The 5% maximum principle strain criterion predicts the maximum load very close to maximum load obtained using the elasto-plastic material. When using the isotropic hardening model, the maximum principal strain was approximately 27 % at the maximum load.

The FE mesh and the material models used are rather practical for every day practice but it has to be emphasised that the models predict the upper level of the maximum load because no influence of welding is considered in the model. Therefore it is necessary to calibrate such “equivalent” FE model, especially when the isotropic-hardening constitutive model is used, with results obtained on full scale tests. Alternatively, the results obtained from tests on the critical components, for example the nozzle test presented above, are useful to predict the strain at the maximum load. The results obtained at LTU indicated that the resultant strain was approximately 12% at the maximum load in the model when von Mises yield criterion was used, Fig.8.d.

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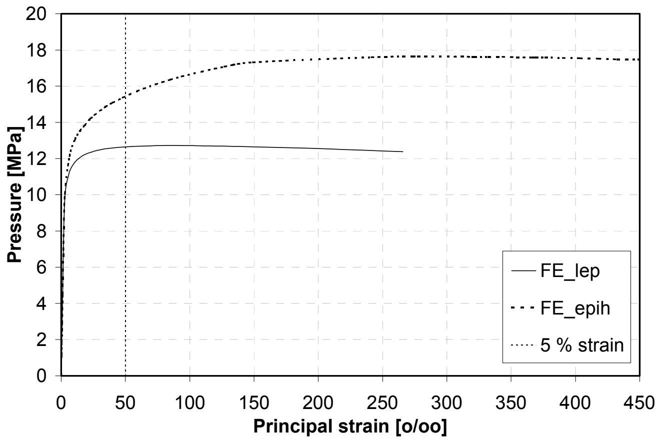


**Fig. 10** *Influence of the constitutive model on the maximum load prediction*

## 7. DISCUSSION AND CONCLUSIONS

1. The penalisation of von Mises yield criterion is based on the maximum ratio of the von Mises equivalent stress to the Tresca equivalent stress for the same load, which always leads to conservative results. This assumes also that Tresca's yield criterion is better approximation than von Mises' yield criteria. Investigation carried out at LTU [9] using biaxial specimens indicates that Mises' yield criterion is rather adequate choice for EN 1.4462.

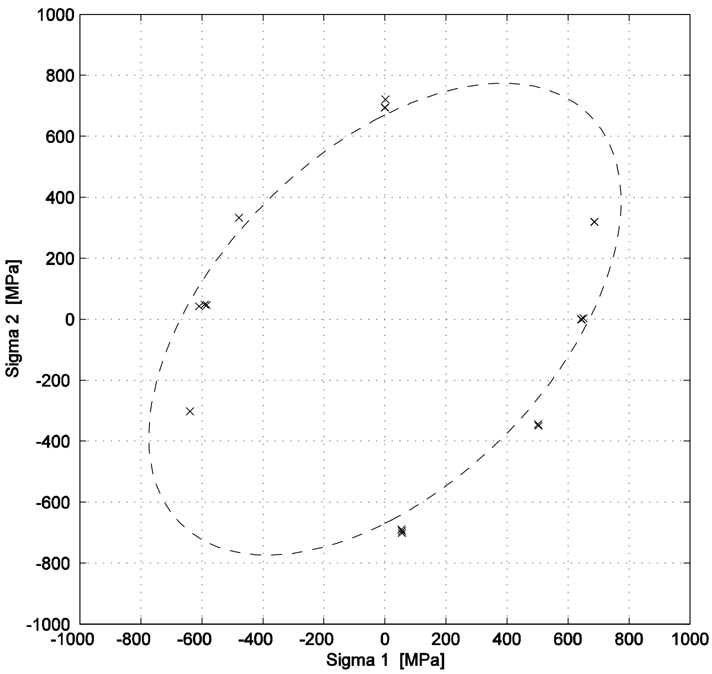


**Fig. 11** *Stress points corresponding to 0.2% plastic offset strain and the approximation using von Mises yield criterion [9]*

2. Comparison between membrane tests with the plain plate and numerical results indicates reliability of the FE model which was created on more optimistic assumptions than given in [8] and [10]. The isotropic hardening and von Mises yield criterion led to very good agreement with the experimental results. Results obtained on the membrane with the welded nozzle clearly show the

importance of the weld quality on the performance of the detail. Imperfections in the weld was not modelled which resulted in unreliable prediction of the maximum load. However, the behaviour of the specimens was predicted rather well, until the failure in the weld. This FE model suggests the 12% of the resultant strain as the strain limit due to the welding.

3. FE prediction of the maximum load obtained in the simple example using isotropic hardening in comparison to ideal plastic constitutive model justify further research towards the economic design of pressure vessels made of Duplex 2205. The best possible way to gain more confidence in the modelling is to compare numerical results with a full scale test of a pressure vessel. The tests performed on the critical details, such as "membrane tests" presented here, demonstrate the more economic alternative to increase the knowledge related to the behaviour of pressure vessels.

4. The elongation $A_5$ of Duplex 2205 was between 31% and 40% in uniaxial coupon tests performed at LTU. This leads to the conclusion of an inadequate and disadvantageous classification of Duplex 2205 as a ferritic steel as it is in the current practice when DBA-DR is used for design.

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