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Experimental and Numerical Analysis of Aluminium Columns Subjected to Fire

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ABSTRACT

An experimental investigation is undertaken in order to study the behaviour of AA 6082 alloy aluminium columns at elevated temperatures. Particular emphasis is put on high temperature creep effects. Tensile tests provide information for the material model of aluminium applied in the nonlinear finite element programs. 31 column buckling tests are performed for validation of the material models in nonlinear finite element programs and for evaluation of design rules. The column buckling tests are compared to numerical analyses and design rules predictions.

KEY WORDS: Fire, experiment, aluminium

INTRODUCTION

The cost and weight benefits that may be achieved by utilizing aluminium alloys in offshore structures are becoming well known. Some of the latest examples are the living quarters of the Visund, Oseberg Øst and Troll C platforms in the North Sea. Oseberg Sør, which is under construction will also be provided with living quarters built in aluminium. The aluminium alloy AA 6082 is frequently used. The choice of this alloy is based on a combination of high strength and good resistance to corrosion, in addition to the availability of different forms, e. g. extruded profiles and plates.

Accidental fires are events with severe catastrophe potential, in particular for aluminium structures, due to the rapid strength degradation of aluminium at elevated temperatures. Personnel must be able to reach the rescue areas and remain safe there until evacuation is performed. This requires that the structure can not collapse before evacuation is carried out. Reliable fire response prediction models are essential for the design and fire safety assessment. Experimental tests are needed to evaluate material models for aluminium under elevated temperatures.

When design rules are evaluated in this work, the focus is set on the capacity of columns subjected to axial compression, bending and temperature load / fire. Capacity both at ambient temperature and elevated temperatures are checked. The material properties (yield strength, ultimate strength and ductility) at elevated temperatures are also checked.

Design rules for steel structures subjected to fire are based on comprehensive testing and long experience. When it comes to aluminium structures, there are less design rules and data / test results available. The test results in this work are compared to predictions from three different design codes: NS 3471, BS 8118 and ENV 1999 which is the prestandard for Eurocode 9.

The collapse process for frame structures with redundancy, will lead to variable force conditions for the individual beam-column components. During a fire, some structural components might collapse at an early stage and shed forces to surrounding members that still have some reserve capacity. These members may remain highly utilized at high temperatures for a considerable time, and it becomes important to evaluate the effect of creep, preferably for various stress levels.

Typically, design is based on reduced values for the material properties for aluminium at elevated temperatures. This approach needs to be verified through tests and numerical analyses. The computer programs USFOS and ABAQUS are used for this verification.

The different tempers in aluminium alloys bring another challenge : Some tempers rapidly loose their strength at elevated temperatures, others will degrade slowly while some tempers even gain strength. Tensile tests conducted at elevated temperatures are needed to gain more knowledge in this respect.

Aluminium structures subjected to fire could experience a long period at elevated temperature. Therefore creep should be taken into account. Creep depends of the stress level, the temperature level and the time the material is subjected to these loads.

There still is a need for more tests on aluminium components and structures to be carried out. The development of design codes has revealed a lack of available tests results for aluminium. There is also a need for more data of material properties at elevated temperatures.

MATERIALS AND METHODS

Specimens

The test specimens are fabricated from rectangular hollow sections with nominal width and height equal to 120 mm and thickness of 7 mm. The length of the specimens is 2100 mm, corresponding to a slenderness of $\lambda = 41$. The present study is restricted to the alloy AA 6082 (AlMgSi1), which has high strength in the fully heat-treated condition. Due to its favourable resistance to corrosion, this alloy is frequently used in offshore structures. The two tempers T6 and T4 are included in the tests. The temper T6 corresponds to quenching from extrusion temperature and subsequently artificial aging. In the T4 condition the profiles are not artificially aged, but otherwise treated identically to the T6 series. Some of the columns have transverse welds. These columns were cut into two equal sections and welded together. An overview of all specimens are given in Appendix.

Control measurements of the specimens were made. Initial imperfections (out-of-straightness) are negligible. The specimens have imperfections less than 1 mm.

Experimental Procedure

The experimental setup and test results are described in detail in Langhelle et al (1996) and Langhelle (1998). The column is attached to a spherical surface at the end to ensure pinned end condition. The effective length is 1906 mm. The load is applied with an eccentricity of 8 mm.

The specimens are heated by use of electrical resistance heating elements. Insulation elements are used to minimize the heat loss to the surroundings, and to obtain homogenous temperature conditions along the specimen.

The following data are recorded during the tests: Axial force, axial compression, lateral deflection of the mid section of the specimen and the temperature distribution along the specimen

EXPERIMENTAL RESULTS

For convenience the following definitions are made: ***T4*** denotes columns of temper T4 with wall thickness 7 mm. ***T67*** denotes columns of temper T6 with wall thickness 7 mm. ***T65*** denotes columns of temper T6 with wall thickness 5 mm

Buckling Tests at Ambient Temperature

Buckling tests conducted at ambient temperature are conducted to provide a reference for the other tests at elevated temperatures. The results of the tests in terms of collapse stress and buckling load are presented in Appendix in Table 1. Relation between axial load and axial compression of ***T67*** are presented in Figure 1, which also shows that local wall buckling takes place after the global buckling. The local buckling occurs earlier in the post buckling range than for ***T4***.

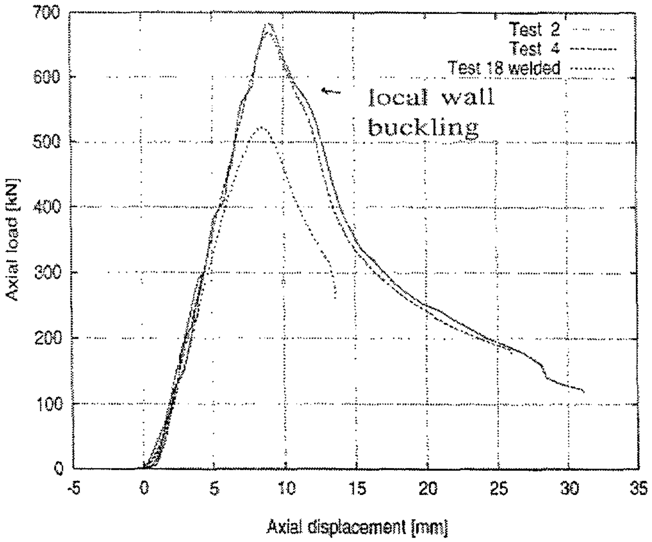

Figure 1 Buckling behaviour of ***T67*** at ambient temperature.

The two unwelded ***T67*** have a difference in capacity of 14 kN. As shown in Figure 1, the introduction of a transverse weld in test no 18 affects the buckling capacity of ***T67*** significantly. The capacity decreases by approximately 23 % which is attributed to the reduced strength in the heat affected zone. In addition, the ductility is dramatically reduced due to brittle fracture in the weld, which takes place at moderate lateral deformations. It should, however, be noted that lack of through-thickness welding may have accelerated the fracture.

Large rotations occur at the plastic hinge prior to rupture for the unwelded columns. Generally, ***T4*** experience a more ductile behaviour than ***T65*** and ***T67***, allowing larger global deflections. In addition initiation of local buckling of ***T4*** is observed during loading of the columns and is fully developed after the maximum capacity is reached. Initiation of local buckles of ***T65*** and ***T67*** is first observed in the post collapse range. This causes a sudden loss of capacity, especially for ***T65***.

Buckling Tests with Constant Heating Rate

Two different heating rates (5 and 12 °C/min) and two stress levels (75 and 110 MPa) are applied to check the influence of creep on the ultimate strength. Some of the columns are fabricated with transverse welds at the mid section to investigate how the weld and heat affected zone affect the capacity.

The following definitions are applied: ***Reference temperature*** is the average temperature at the midsection of the column. ***Critical temperature*** is the reference temperature as the axial force starts to drop. ***Constant heating rate*** is the heating rate from the reference temperature is passing 40 °C until the critical temperature is reached.

Results are presented in table 2 in Appendix. The relationship between global deflection and temperature are presented in Figure 2 for columns of temper T4.

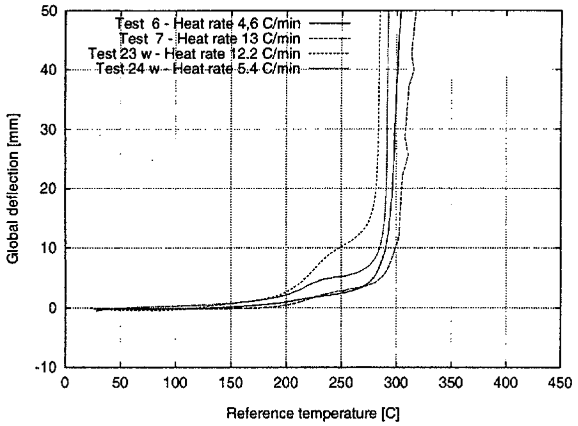

Figure 2 Temper T4 columns tested at 75 MPa

Both welded and unwelded columns have similar critical temperatures, independent of the applied heating rates. This is similar to the behaviour experienced at ambient temperature and implies that creep is not present.

Buckling Tests at Constant Temperature

For frame structures with some redundancy, the individual beam-column components may experience variable force conditions during the collapse process. When subjected to heating, some structural components will collapse at an early stage and shed the forces to surrounding members that still have some reserve capacity. Consequently, it is important to evaluate the effects of creep also for variable stress conditions in combination with high temperatures.

Table 3 in Appendix displays an overview of the test results. The heating rate is approximately 12 [°C/min] for all these tests. Figure 3 presents the loading history and creep deformations. The creep deformation is described by the increase in lateral deflection while the stress is kept constant.

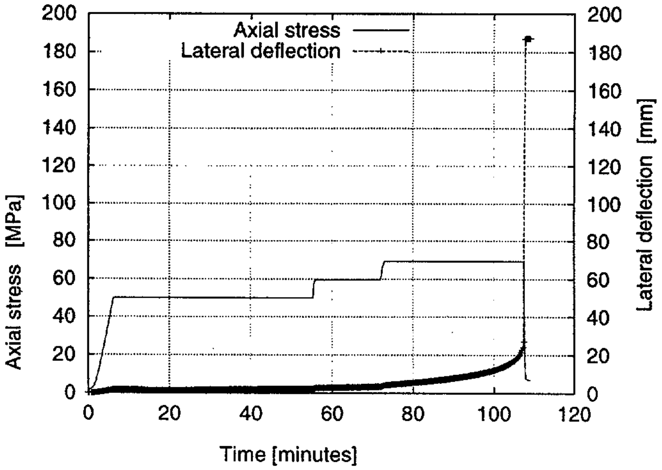

Figure 3 Axial load and lateral deflection versus time for test T65 / 31.

Creep deformation is observed at 60 MPa, but the development is slow. When the stress is increased to 69 MPa, the creep deformations accelerate. It is shown in Figure 3 how the creep deformations develop during the last stress level, which is held for approximately 35 minutes.

DISCUSSION

Based on the tests in this study, the critical temperatures are not found to be significantly dependent on the heating rates. This implies that creep effects are small for the parameter range investigated. It is also observed that columns of both tempers yield similar capacity at approximately 285 °C.

While no creep is observed for the tests conducted with constant heating rates, the columns tested at constant temperature experience creep deformations. The creep deformations depend on the temperature and stress level. The presence of creep reduces the collapse stresses. It is also observed that both tempers yield similar collapse stresses at approximately 200 °C, due to changes in material properties caused by the long heating periods. The observations of creep for the columns tested at elevated temperatures correspond to observations made by Aasen and Larsen (1991).

Welded columns seem to behave more ductile at elevated temperatures. This observation is relevant for both tempers. At ambient temperature, fractures in the welds take place at moderate lateral deformation, compared to the unwelded columns. This difference is not present at elevated temperatures, where the lateral deformations for welded and unwelded columns are similar.

There is no difference in capacity between welded and unwelded columns of temper T4 at any temperature. The capacity of welded columns of temper T6 changes from pronounced lower capacity than unwelded columns at ambient temperature, to no difference in capacity between welded and unwelded columns at 285 °C. Welded columns of both tempers seem to behave more ductile at elevated temperatures.

It is emphasized that creep is time, stress and temperature dependent. Therefore changes in any of these parameters will affect the creep behaviour. The test results presented are therefore directly connected to the test conditions applied in the tests.

COMPARISON OF TESTS AND DESIGN CODES

The following design codes are used : NS 3471, BS 8118 (only for room temperature) and ENV 1999 (Eurocode 9). The test results are compared to capacity predictions according to the design codes. The calculations are based on an axial force eccentricity of 8 mm and an effective length of 1906 mm. All material and safety factors are set equal to 1.0. The critical temperatures measured in the tests are used as design temperature when calculating the buckling stress according to the design codes. A comparison is given here in Figure 4, 5 and 6. Complete results are given in Table 1, 2 and 3 in Appendix. The comparison is conducted on specimens of temper T6 with a wall thickness of 7 mm.

Tests Conducted at Room Temperature

The nominal code capacity is lower than the collapse stress for both unwelded and welded columns, see Figure 4. Differences in nominal code capacities are observed despite almost similar yield strength in the different design codes.

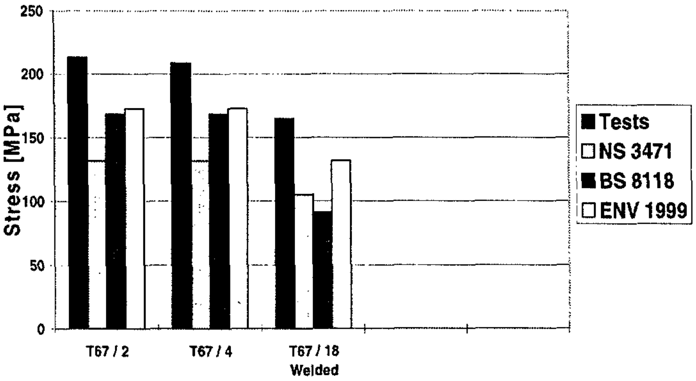

Figure 4 Test capacities and nominal code capacities for ***T67*** at room temperature.

The code capacities for the welded columns reflect the reduction coefficients applied in the design codes for NS 3471 and BS 8118. The reduction coefficient is largest for BS 8118.

Tests Conducted with Constant Heating Rate

The two tests for unwelded columns conducted at stress level of 75 MPa experienced different critical temperatures. It is not known what caused the unexpected low critical temperature of 270 °C for one of the columns. The test capacity of this column is lower than nominal code capacity according to NS 3471. Test capacities for all other columns are larger than nominal code capacities. The difference is particularly large for the welded columns, most pronounced at the lowest temperature, refer Figure 5.

For unwelded ***T67***, the nominal code capacities according to ENV 1999 are even lower than the nominal code capacity according to NS 3471. These capacities were similar at ambient temperature. The distinction in capacities at elevated temperatures corresponds well to the differences in yield strength. Both design codes have similar yield strength at ambient temperature.

The nominal code capacities according to NS 3471 are also largest for welded ***T67***, except for the column with a collapse temperature of 223 °C. Again, this distinction is due to different yield strength reduction.

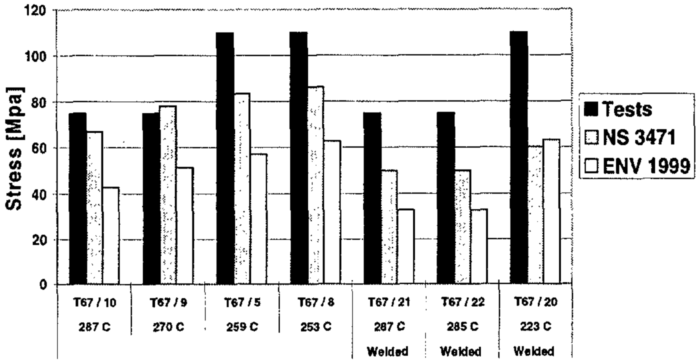

Figure 5 Test capacities and nominal code capacities for ***T67*** with constant heating rates.

Tests Conducted at Constant Temperature

Nominal code capacities and test capacities are presented in Figure 6. The nominal code capacities are higher than the test capacities at temperatures above 250 °C and lower at 204 °C. For ENV 1999, nominal code capacity is always lower than the test capacity.

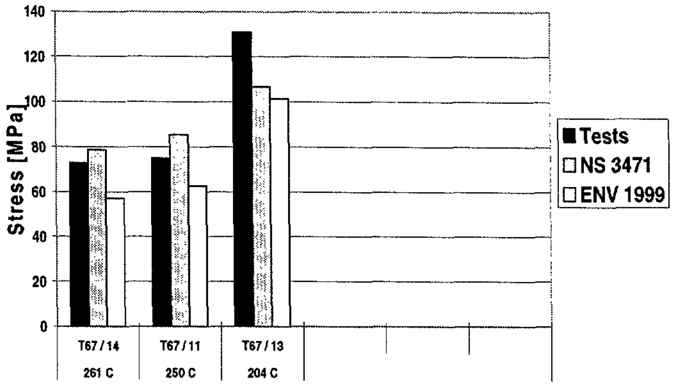

Figure 6 Test capacities and nominal code capacities for ***T67*** at constant temperature.

DISCUSSION OF TEST RESULTS AND DESIGN CODES

Predictions according to NS 3471 yield reasonable results for all columns, except for those tested at constant temperature above 250 °C. Creep is present in these tests, but the standard does not take creep into account, therefore giving non-conservative results. The design code yields most conservative results for welded columns of temper T6, especially for the highest temperatures. Tensile tests conducted by Langhelle (1998), indicate that different reduction coefficients for yield strength at elevated temperatures should be applied for temper T4 and T6 (the design code gives similar reduction coefficients for both tempers). A more comprehensive study and more tensile tests should be conducted to establish these coefficients.

BS 8118 yields conservative predictions for welded columns of temper T6, otherwise the predictions are similar to the tests. These observations cover only ambient temperature.

ENV 1999 yield reasonable capacities for all columns, except for those tested with constant heating rates. ENV 1999 is the only design code which takes creep into account through the reduction factor 1.2. Creep is developed in all constant temperature tests, most pronounced at the highest stress levels and temperatures. The reduction coefficient for creep is always applied for temperatures above 170 °C.

Creep is not present in the tests with constant heating rate and therefore the applied reduction coefficient yields conservative results. To avoid this source of error, an additional provision for use of the reduction coefficient could be established : The time spent at temperature higher than 170 °C could be specified. If the period is less than 20 minutes, creep can be disregarded, and the reduction coefficient 1.2 could be replaced by 1.0. This suggestion is based on the observations of tests with different constant heating rates, and is strictly relevant only for the stress levels applied in the present study. Additional tests should be conducted before a specified "time limit" could be established.

EXPERIMENTAL RESULTS AND NUMERICAL ANALYSIS

Finite Element Modelling

The specimens are modelled with six beam elements with box profiles, in order to represent the actual temperature distribution sufficiently well. In addition, to the eccentricity of 8 mm, a member out-of-straightness of 1 mm is introduced.

Material properties are based upon measured values, Langhelle (1998). In the ABAQUS analysis, stress - plastic strain curves measured at the various temperatures are applied. In USFOS the material data are calibrated to the measured values, Langhelle (1998). For the intermediate temperatures interpolation is adopted.

In ABAQUS creep is included in the analysis of constant temperature tests. Several models are available, and user-defined models are also possible. A model based on the "power" law (Norton-Bailey) is used. The parameters in this model are determined from tensile tests conducted by Kaspersen and Sørås (1994).

Buckling Tests at Ambient Temperature

As the lateral deflection increases, large plastic deformations form in the region close to the middle section. The plastic deformations are followed by local wall buckling and accompanied by a dramatic reduction in the axial load, see Figure 7.

The specimens experience substantial plastic deformations prior to rupture. Specimens of temper T4 have a more ductile behaviour than specimens of temper T6. Table 1 in Appendix shows the ultimate stress from tests and numerical analysis. Generally the agreement is good. USFOS yields higher collapse stress than ABAQUS and overpredicts the capacity slightly.

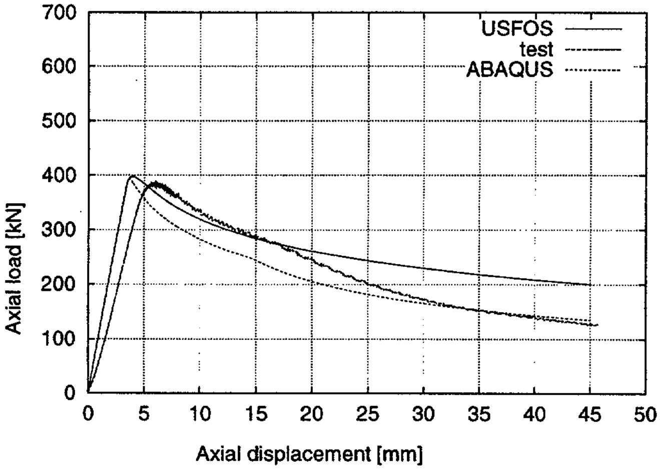

Figure 7 Buckling behaviour of specimen of temper T4 at ambient temperature.

From the axial load - axial compression curves for the various members a discrepancy between the simulated and measured stiffness in the elastic range is observed. This deviation is difficult to explain. However, it is the ultimate load and post collapse area which is of most interest for comparison with numerical analysis. Residual stress from fabrication may cause premature yielding of parts of the cross section, but according to Mazzolani (1985), residual stress of a similar alloy (AA 6063) is negligible when the profiles are extruded and heat treated as these tests specimens are. Stub column tests, which could have shed light on this issue were not performed.

Buckling Tests with Constant Heating Rates

One test on a specimen of temper T4 is presented in Figure 8. It is a welded column with a stress level of 75 Mpa. The ultimate stress for all tests are given in Table 2 in Appendix.

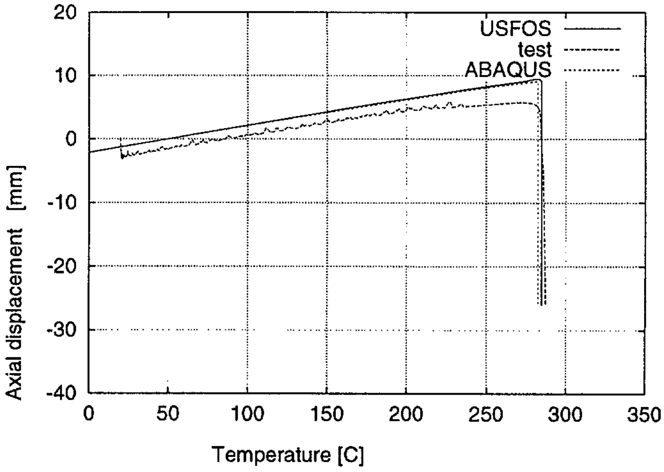

Figure 8 Buckling behaviour of specimen of temper T4 at constant heating rate.

The specimens had similar capacity for both high and low heating rates. This indicates that creep effects are small for the parameter range investigated. It is also noted that even if the T6 and T4 tempers have quite different material characteristics at room temperature, the high temperature buckling behaviour seems to be quite similar. The critical temperatures found in numerical analysis correspond well to the critical temperatures from the tests, see Table 2 in Appendix. A closer description of all the tests are given in Langhelle (1998).

Buckling Tests at Constant Temperature

Tests conducted at constant temperature include creep. A comparison between the test result and numerical predictions is given in Figure 9. The axial displacement which describes the deformation / compression of the column is given along the x-axis, while the axial load applied to the column is given along the y-axis. The creep model in ABAQUS overpredicts the creep at each stress / load level for the parameters used. Since USFOS does not include creep, the capacity is overpredicted.

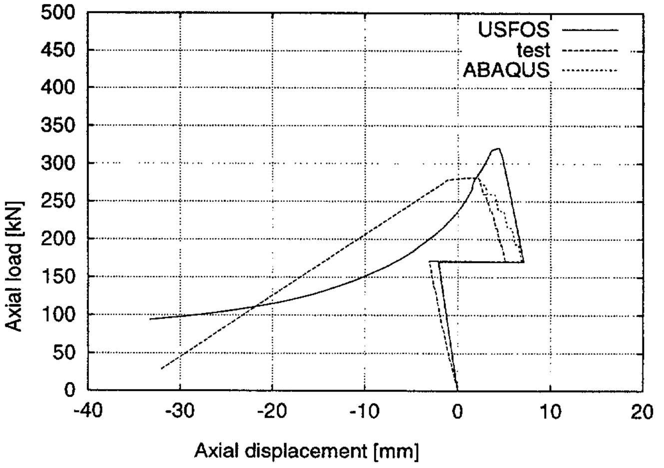

Figure 9 Buckling behaviour of specimen of temper T65/30 at constant elevated temperature.

It should be noted that the collapse stresses quoted in Table 3 in Appendix depend on the holding period and are only relevant for the periods used in the test. If the duration of the test at each load level is increased, it is anticipated that the collapse stresses will be lower.

Discussion of Test Results and Numerical Analysis

There is a good correspondence between tests and numerical analyses at normal temperatures. USFOS yields slightly higher collapse stresses than ABAQUS.

The agreement is also good for tests conducted with constant heating rates. USFOS yields higher critical temperature than ABAQUS, but the deviation is small. No creep effects was observed for the two heating rates applied

Creep is present in the tests at constant temperature and causes a reduction of capacity. The effects of artificial aging and annealing (as described in Langhelle (1998)) may also have impact on the capacity. Artificial aging may have increased the capacity for temper T4, while annealing decreases the capacity for temper T6. Columns of temper T6 and T4 had similar collapse stress when tested at constant temperature and stress, despite of large differences in the capacities at ambient temperature.

Since USFOS does not include creep, the numerical analyses for both temper T4 and temper T6 should always predict a higher collapse stress than measured in the tests conducted at constant temperature. Temper T6 is an artificially aged condition. Further heating could cause annealing, giving a further decrease of the strength of the material. It is however difficult to distinguish between reduction in capacity caused by creep or annealing. The numerical analyses (USFOS) predict higher collapse stress than measured in the tests at both 200 °C and 250 °C for temper T6.

Creep is present for temper T4 (as for temper T6) and the numerical analyses with USFOS for temper T4 should always predict a higher collapse stress than measured. Temper T4 is only naturally aged and the heating applied in the tests could cause artificial aging, Langhelle (1998) and therefore an increase of strength. USFOS predicts lower collapse stresses than measured values for temper T4 tested at constant temperature (Langhelle, 1998). This indicates an increase in strength for the material, probably due to aging.

The collapse stresses predicted by ABAQUS (including creep) for temper T6 correspond well to the collapse stresses measured in the tests. This confirms that the effect of creep gives a large contribution to the capacity for temper T6. When it comes to temper T4, ABAQUS also gives lower collapse stresses than tests. These observations indicate that artificial aging (which increases the strength) affects the capacity more than creep does for temper T4.

Creep analyses with ABAQUS at 200 °C give acceptable results. This calibration is based on five creep tensile tests at 200 °C, with stress levels and test periods similar to the column tests, Langhelle (1998). Tertiary creep influenced the calibration of the creep model at 250 °C, Langhelle (1998).

CONCLUSIONS

The main objectives of this work has been to conduct tests which could contribute to the data base of column buckling tests at ambient and elevated temperatures. The test results are used to validate nonlinear finite element analysis models. These models may be used in design of aluminium structures exposed to fire. Mechanical properties obtained in tensile tests are applied to calibrate the nonlinear finite element models. The column buckling tests are also applied for validation of design codes for aluminium structures.

The tests conducted at ambient temperature are used as a reference tests for the tests conducted at elevated temperatures. Welded columns of temper T4 experience no loss of capacity, while temper T6 columns get a pronounced loss of capacity.

Columns of temper T6 have a much higher capacity than temper T4 at ambient temperature. At elevated temperatures, the loss of strength is most pronounced for temper T6. This results in virtually identical capacities for columns of both tempers at approximately 285 °C. When columns of temper T6 is welded, the capacity is reduced. The reduction is not observed when the temperature has reached 285 °C. It may therefor be concluded that the strength is invariant with respect to temper at 285 °C, and welding of a column does not affect the capacity at this temperature. Thus the importance of temper and weld at ambient temperature gradually vanishes with increasing temperatures, which is beneficial for aluminium structures subjected to fire.

Whereas creep is not observed at constant heating rates, it takes place in columns of both tempers tested at constant temperature. The creep development depends on the time, stress and temperature applied in the tests. Therefore changes in any of these parameters will affect the creep behaviour. The test results presented in this work are therefore directly connected to the test conditions applied in the tests and may not be relevant for different conditions.

ENV 1999 (prestandard for Eurocode 9) gives good results for columns at constant temperature and normal temperature, but conservative results for the columns tested at a substantial heating rate. The code takes creep implicitly into account through a reduction coefficient applied for all temperatures above 170 °C. Creep is not present for these tests. To avoid this source of error, an additional assumption for applying the reduction coefficient could be specified. Additional tests are needed before a "time limit" could be specified, but the tests in this work indicate that no creep was present provided that the duration of the high temperature (higher than 170 °C) was less than 20 minutes.

The numerical analyses conducted with USFOS and ABAQUS confirm that these programs are well suited for column buckling tests at constant heating rates, but much work remains for the creep model. Further tests should be conducted to obtain a more comprehensive database for creep tensile tests.

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APPENDIX

Table 1 Test results, design codes and numerical analysis – room temperature

Tests			Design code [MPa]			Numeric. Anal [MPa]	
Temp. / Test no	Buckl. load [kN]	Collap. stress [MPa]	NS 3471	BS 8118	ENV 1999	USF	ABA
T4/1	388	122	75	85	77	126	124
T4/3	391	123	75	85	77	126	124
T4/7 1)	385	122	75	85	77	126	124
T67/2	683	216	130	167	170	219	207
T67/4	669	211	130	167	170	219	207
T67/18 1)	522	165	110	88	135	175	163
T65/26	448	195	132	166	168	218	200
T65/27	506	220	132	166	168	218	200

1) Welded

Table 2 Test results, design codes and numerical analysis – constant heating rate

Tests				Design code [MPa]		Numeric. Anal [°C]	
Temp. / Test no	Stress level [MPa]	Heat. rate [°C/min]	Crit. temp [°C]	NS 3471	ENV 1999	USFO	ABA
T4/ 6	75	4.6	286	30	---	285	282
T4/7	75	13.0	290	30	---	285	282
T4/19	102	4.7	157	67	---	210	270
T4/23 1)	75	12.2	283	30	---	285	282
T4/24 1)	75	5.4	290	30	---	285	282
T67/10	75	5.0	287	68	43	287	285
T67/ 9	75	12.0	270	78	52	287	285
T67/5	110	4.7	259	83	57	249	244
T67/8	110	12.4	253	87	63	249	244
T67/21 1)	75	4.9	287	50	32	287	285
T67/22 1)	75	11.1	285	50	33	287	285
T67/20 1)	110	3.8	223	60	63	228	213
T65/29	75	4.7	276	68	46	275	263
T65/28	110	4.7	241	98	77	254	244

1) Welded

Table 3 Test results, design codes and numerical analysis – constant temperature

Tests				Design code [MPa]		Numeric. Anal [MPa]	
Temp. / Test no	Init.stress / incr [MPa]	Tmp [°C]	Coll. stress [MPa]	NS 3471	ENV 1999	USF	AB
T4/16	50/ 9.5/4.5	259	64	41	---	118	59
T4/15	75 9.6/ 4.7 / 8	210	123	57	---	103	124
T4/12	75 / 9.5	198	131	60	---	108	121
T4/25 1)	75 / 9.5	223	112	53	---	128	118
T67/14	50 / 10	261	73	79	57	99	59
T67/11	75 / 12.7	225 / 250	75	85	62	109	75
T67/13	75 / 10	204	131	108	102	155	128
T65/31	50 / 9.6	264	69	76	52	85	59
T65/30	75 / 9.6	222	122	100	79	139	119

1) Welded