07

Sendt pr email 21/4.

COMPARATIVE STUDY BETWEEN NUMERICAL MODELS AND BUCKLING TESTS OF ALUMINIUM COLUMNS AT ELEVATED TEMPERATURES

Nina Kristin Langhelle
Department of Marine Structures
Norwegian University of Science and Technology
Trondheim
Norway

Ernst Eberg
Byggcon a.s.
Bodø
Norway

Jørgen Amdahl
Department of Marine Structures
Norwegian University of Science and Technology
Trondheim
Norway

ABSTRACT

Aluminium is frequently used in offshore structures due to its light weight and corrosive resistance. For all offshore structures, accidental fires are events with severe catastrophe potential. Due to the rapid strength degradation at elevated temperatures, this is particularly true for aluminium structures. Reliable fire response prediction models are essential for the design and fire safety assessment. Experimental tests are needed to evaluate strength models for aluminium under elevated temperatures.

In the present study state-of-the-art material and FEM models for aluminium frame structures are correlated to experimental data obtained in tests carried out at the Norwegian University of Science and Technology and SINTEF Structural Engineering. The tests include AA 6082 alloy aluminium columns at ambient and elevated temperatures. Some of the tests at elevated temperatures are carried out at constant load with increasing temperature, while other tests experienced constant temperature and increasing load.

The test results of columns of the tempers T4 and T6 are compared with results from analysis with the computer programs USFOS (Ultimate Strength analysis of Framed Offshore Structures) and ABAQUS. Analysis and tests yield similar collapse loads, while some divergence are found for axial compression and lateral deflection.

INTRODUCTION

The cost and weight benefits that may be achieved by utilizing aluminium alloys in offshore structures are becoming well known. One of the recent examples is the living quarters of Snorre tension leg platform in the North Sea.

Accidental fires are events with severe catastrophic potential, in particular for aluminium structures, due to the rapid strength degradation of aluminium at elevated temperatures. Accurate prediction of fire resistance is therefore essential. Experimental tests are needed to evaluate the material models for aluminium under elevated temperatures.

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 the forces to surrounding members that still have some reserve capacity. These members may therefor remain highly utilized at high temperatures for a considerable time, and it becomes important to evaluate the effect of creep, preferably for various stresses.

Some tests on aluminium beams and columns at elevated temperatures have been found (Broli and Møllersen (1985), Fosse and Bjoland(1986), Walaas(1991), Langhelle (1992)).

Several buckling tests of aluminium columns at ambient temperature have been conducted (Valtinat and Dangelmaier (1982), Mazzolani and Valtinat (1987), Hong (1987), Capelli, De Martion and Mazzolani (1987), Nethercot (1987), Lai (1988)).

Creep test results with long holding periods and small loads are available, but creep test results for small holding periods and high load are more rare.

Typically the design is based on reduced values for the material properties for aluminium at elevated temperatures. This approach therefore 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 to the computer programs. Some tempers rapidly loose their strength in elevated temperatures, others will slowly loose their strength while some tempers even gain strength.

Aluminium structures subjected to fire could experience a long period at elevated temperature. Therefor 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.

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. This corresponds to a slenderness equal to $\lambda = 41$ for the specimen positioned in the experimental setup. The present study is restricted to the alloy AA 6082 (AlMgSi1), which has high strength in the fully heat-treated condition. Due to the 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.

Control measurements of the specimens were made. Initial imperfections (out-of-straightness) are negligible. The specimens have imperfections less than 1 mm. 31 tests have been conducted.

Experimental Procedure

The experimental setup and test results are described in detail in Langhelle et al (1996) and Langhelle (1998). Pinned end condition is used, one end is free axially. 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 compression and the temperature distribution along the specimen.

FINITE ELEMENT MODELLING

The specimens are modelled with six beam elements with box profiles. In order to represent the actual thermal expansion, the temperature distribution from the test are used. One beam element would as such be sufficient in USFOS analysis for a beam with homogenous properties and temperature.The temperature distribution shows a decay towards the ends, and it is therefor necessary to apply more elements to take care of this temperature distribution. While the temperature is given for the element in USFOS, it is given in the nodes for ABAQUS.

The load is applied with an eccentricity of 8 mm. In addition member out-of-straightness of 1 mm is introduced, corresponding to control measurements of all specimens prior to testing.

The material properties in ABAQUS and USFOS are based upon measured values given in Table 1 in appendix. 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 in Table 1. For the intermediate temperatures interpolation is adopted.

The material model used in USFOS is based upon the plastic hinge concept, where the yield criterion is formulated in stress-resultants. Two surfaces are used, Mroz (1969). The bounding surface represents full plastic utilization of the cross-section, the first yield surface, which is identical shaped but smaller, limits the elastic domain.In the elastic range tangential stiffness matrices are modified according to plastic flow theory. In the elastic-plastic range a gradual transition to fully plastic behaviour is performed according to the position of the stress state relative to the bounding surface. The size of the yield surface and the rate of plastification in the elasto-plastic range are free parameters that can be calibrated to give a close fit to measured uni-axial stress strain curves.

ABAQUS is a widely used general purpose program. The material model is stress-strain based. Modifications for plasticity is performed according to uniaxial stress-strain relationship. In the present work measured values are used.

In ABAQUS creep in included for the analysis with constant elevated temperature. 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 strain tests Kaspersen and Søräs (1994).

EXPERIMENTAL RESULTS AND NUMERICAL ANALYSIS

Buckling Tests at Ambient Temperature

Six buckling tests are carried out at ambient temperature to provide a reference for the behaviour at elevated temperatures. The test results of two specimens are presented. The test results are given in Table 2a in Appendix.

Overall elasto-plastic buckling governs the behaviour of the columns at ambient temperature. However, 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 1a and 1b.

The specimens experience large plastic deformations before rupture occurs. Specimens of temper T4 have a more ductile behaviour than specimens of temper T6. Table 2a 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.

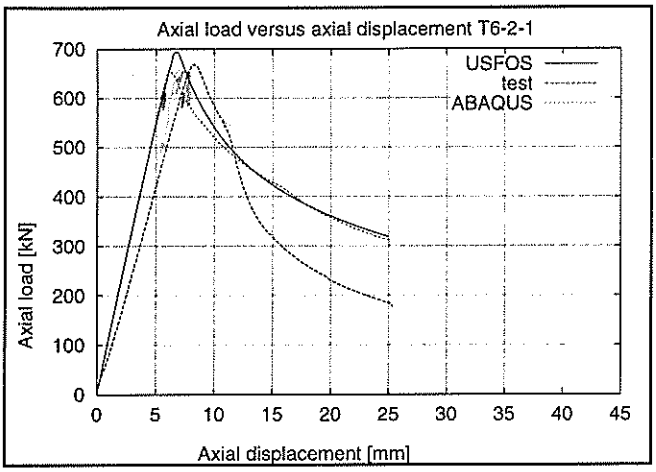

Figure 1a Buckling behaviour of specimen of temper T6 at ambient temperature.

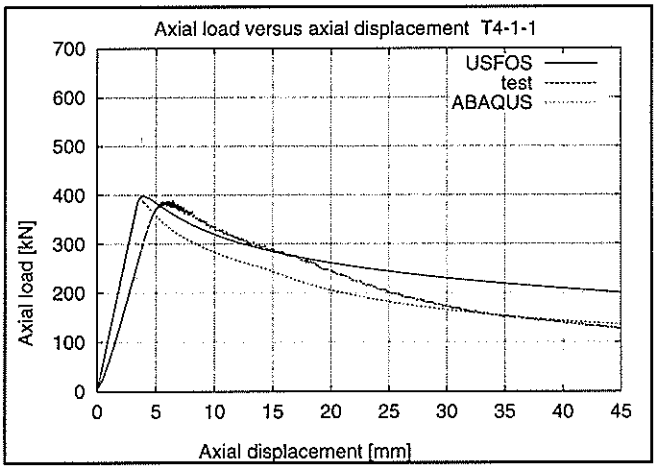

Figure 1b Buckling behaviour of specimen of temper T4 at ambient temperature.

From the axial load - axial compression curves for the various members there is observed a discrepancy between the simulated an measured stiffness in the elastic range. This deviation is difficult to explain with certainty, 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) are negliable 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 however not taken.

Buckling Tests at Constant Temperature Rate

14 tests were conducted, 5 of temper T4 and 9 of temper T6. Most of the specimens of temper T4 were preloaded to 75 MPa prior to test, while specimens of temper T6 were preloaded to 110 MPa. To examine the effect of creep on the column buckling behaviour, two different heating rates were used. The

heating was started at pre-defined rate. The test was terminated when buckling or rupture occurred. The critical temperature is defined as the average temperature at mid section as the axial force starts to drop. Two of the tests are presented. The test results are given in Table 2b in Appendix.The critical temperature of the T6 specimens detected in numerical analysis were slightly below the test results. ABAQUS yields a critical temperature 6% and USFOS 4% below the critical temperature. The critical temperature for the specimen T4 is similar to the critical temperatures found in the numerical analysis.

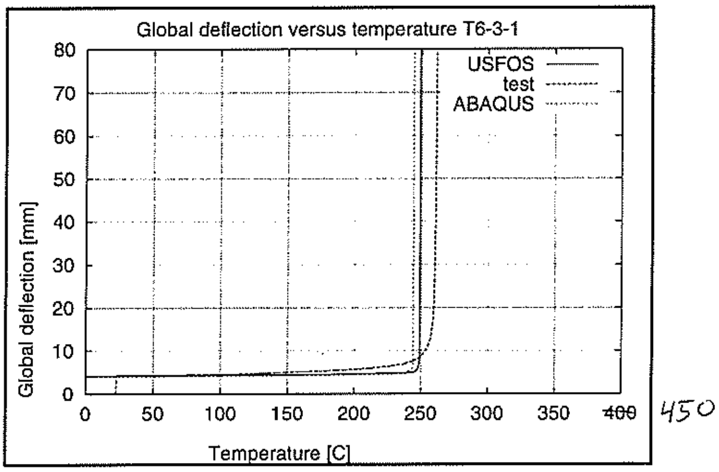

Figure 2a Buckling behaviour of specimen of temper T6 at constant heating rate.

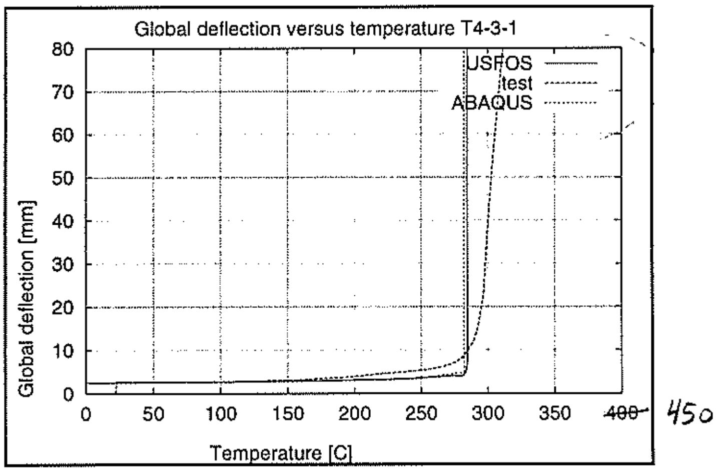

Figure 2b Buckling behaviour of specimen of temper T4 at constant heating rate.

The specimens tested at constant heating rates had similar capacity for both high and low heating rates. This implies that the 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.

Buckling Tests at Constant Temperature

The temperature is kept constant to make it possible to quantify the level of creep deformations that occur at increasing levels of axial stress. The following test procedure is established for the tests: The specimen is loaded to its initial stress level. Thereafter the heating with pre-defined rate is started, and is continued until the pre-defined temperature level is attained.The temperature and stress levels are held for fifteen minutes. Then the load is increased, and the stress level is held constant for fifteen minutes. This increase in stress level is repeated until collapse occur. The test results are given in Table 2c in Appendix. Axial load - axial compression curves for the constant temperature creep buckling tests are presented in Figures 3a, and 3b. Generally, very little creep is observed except for the last load level in each test. This indicates that creep is very stress dependent.

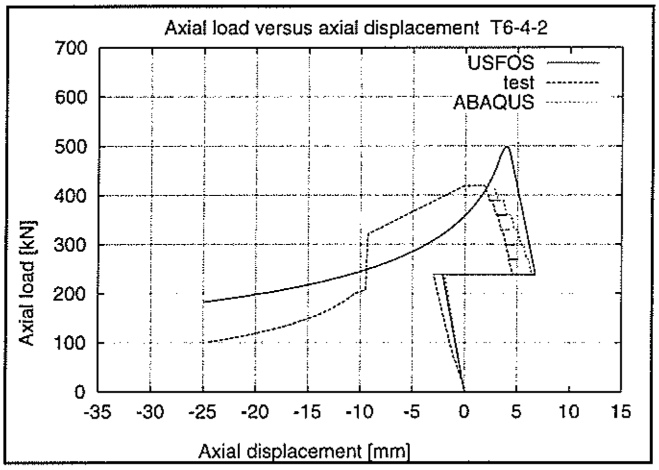

Figure 3a Axial load versus axial compression for test of temper T6 preloaded to 100 MPa.

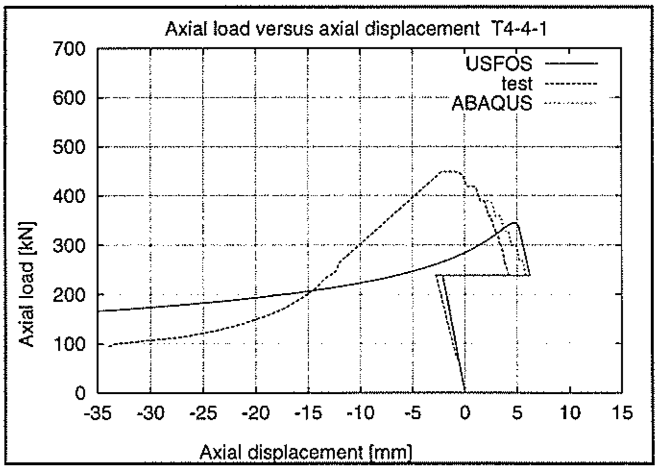

Figure 3b Axial load versus axial compression for test of temper T4 preloaded to 75 MPa

The buckling tests at constant temperature gave similar capacity for temper T4 and T6. This indicates that the beneficial effect of artificial aging of temper T6 is lost, or temper T4 has gained strength, or both these processes of "heat treatment" have taken place. The tests lasted up to three hours.

These conditions correspond to partial annealing (200-300 deg C) and reduces the capacity of the material. Artificial aging, which increases the strength of the material, takes place at 185 deg and usually lasts for 6 hours, Altenpohl (1982). The test of specimen of temper T6 was conducted at 204 deg C, and temper T4 at 198 deg C.

It should be noted that the collapse stresses quoted in Table 2c depends upon the holding period and are only relevant for those 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. It is very difficult, however, to quantify the contribution from creep and loss of artificial aging only from the buckling tests.

Discussion of Test Results and Numerical Analysis

It was concluded in Langhelle et at (1996) that creep was only present in tests at constant temperature level. This conclusion was based on a comparison of test results and calculations according to several design codes.

Both USFOS and ABAQUS overpredict the capacity slightly for temper T6 and T4 at normal temperatures. As shown in table 2a, USFOS yields higher collapse stress than ABAQUS.

For tests at constant heating rates, USFOS yields higher critical temperature than ABAQUS, but the deviation is small. The critical temperatures obtained in the numerical analysis are lower than the test results.Creep is not included in the numerical analysis and confirms the experimental observation of no influence of creep. If creep was included in the analysis, the critical temperatures would have been reduced. Both USFOS and ABAQUS underpredicts the critical temperature.

Strain tests of specimens of temper T4 and T6 were conducted after kept at 200 deg C in a stress free condition for time periods corresponding to duration of the tests conducted at constant temperature. The test results are used in the material models for the numerical analyses at constant temperature. These strain tests should give a correct material model which includes effects of "heat treatment" in the numerical analysis. The strain tests do not include creep, as they are in a stress free condition until the strain test is started.

Creep is present for tests at constant temperature. Since USFOS does not include creep, the collapse load for temper T6 is overpredicted. ABAQUS includes creep and the critical stress for temper T6 agrees well with test results. For temper T4, USFOS underpredicts the collapse load. The reduction of capacity caused by creep (as for temper T6) is much lower than the increased capacity caused by artificial aging. For temper T4, also ABAQUS underpredicts the collapse load.

CONCLUDING REMARKS

The present study provides data for evaluating the impact of high temperature on the buckling of aluminum column. In addition qualitative information of the influence of creep deformations on high temperature buckling behaviour of aluminium beam-columns is investigated. .

The results presented show that the influence of creep strongly depends on the load and temperature conditions the beam-column is exposed to:

The numerical analysis in USFOS and ABAQUS correspond well to tests conducted at room temperature and tests with constant heating rates. For tests conducted at constant temperature (including creep) only the test results of temper T6 show good agreement to the numerical analysis in ABAQUS.

REFERENCES

Altenpohl, D., 1992, "Aluminium Viewed form Within", ISBN 3-87017-138-3, Aluminium-Verlag, Dusseldorf, Germany.

Broli, T. and Møllersen, S., 1985, "Brannbelastede Aluminiumssøyler", Diploma Thesis, Department of Steel Structures, The Norwegian Institute of Technology, Trondheim, Norway.

Capelli, M., De Martino, A. and Mazzolani, F.M.,1987, "Ultimate Bending Moment Evaluation for Aluminium Alloy Members : A Comparison among Different Definitions.", Paper printed in "Aluminium Structures, Advances, Design and Construction", edited by R. Narayanan, Reader in Civil and Structural Engineering, University College, Cardiff, UK.

Fosse, A. and Bjoland, L., 1986, "Brannbelastede aluminiumssøyler", Diploma Thesis, Department of Steel Structures, The Norwegian Institute of Technology, Trondheim, Norway.

Hong, G.M., 1987, "Aluminium Column Curves", paper printed in "Aluminium Structures, Advances, Design and Construction", edited by R. Narayanan, Reader in Civil and Structural Engineering, University College, Cardiff, England.

Kaspersen, R. and Sørås, A., 1994, "Aluminiumskonstruksjoner utsatt for brannbelastning, Materialoppførsel ved høye temperaturer" (in Norwegian), Department of Structural Engineering, University of Tronheim, The Norwegian Institute of Technology.

Kaspersen, R. and Sørås, A., 1994, "Krypeffekter i brannbelastede aluminiumskonstruksjoner" (in Norwegian),Diploma Thesis, Department of Structural Engineering, University of Tronheim, The Norwegian Institute of Technology.

Lai, W., 1988, "Buckling Strength of Welded and Nonwelded Aluminium Members", Doctoral Thesis, Department of Civil and Structural Engineering, University of Sheffield, UK.

Langhelle, N.K., 1992, "Eksperimentell og teoretisk undersøkelse av aluminiumsrør utsatt for temperaturbelastning", Diploma Thesis, Department of Marine Structures, The Norwegian Institute of Technology, Trondheim, Norway.

Langhelle, N.K., Eberg, E., Amdahl, J. and Lundberg, S., 1996, "Buckling Tests of Aluminium Columns at Elevated Temperatures", paper presented at OMAE 1996, Firence, Italy.

Langhelle, N.K., 1998, to be published.

Mazzolani, F.M. and Valtinat, G., 1987, "ECCS Activity in the Field of Buckling of Aluminium Alloy Members", paper printed in "Aluminium Structures, Advances, Design and Construction", edited by Narayanan, R., Reader in Civil and Structural Engineering, University College, Cardiff, England.

Mroz, Z., 1969, "An Attempt to Describe the Behaviour of Metals under Cyclic Loads Using a More General Work-Hardening Model", Acta Mehcanica, 17, pp199-172.

Nethercot, D.A., 1987, "Aspect of Column Design in the new UK Structural Aluminium Code", paper printed in "Aluminium Structures, Advances, Design and Construction", edited by Narayanan, R., Reader in Civil and Structural Engineering, University College, Cardiff, England.

Valtinat, G. and Dangelmaier, P., 1982, "Columns in Aluminium with Longitudinal and Transversal Welds", Conference : Aluminium Weldments, Munich, 24-26 May 1982, Publ : Aluminium-Verlag GmbH.

Walaas, A.Ø., 1991, "Eksperimentell og numerisk analyse av konstruksjonsrespons ved temperaturlaster", Project, Department of Marine Structures, The Norwegian Institute of Technology, Trondheim, Norway.

APPENDIX

Table 1 Strain tests

Specimen	Temperature [°C]	Proof strength $R_{p0.2}$ [MPa]	Tensile strenght R_m [MPa]	Elongiation [%]
T4	20	183	297	29.5
T4	175	148	212	31
T4	200	142	205	23
T4 *	200	230	230	11
T4	225	174	187	16.5
T4	250	183	184	11.5
T4	275	129	129	14.5
T4	285	95	98	18
T6	20	309	322	14
T6	175	246	247	17.5
T6	200	224	224	15
T6 **	200	214	216	14
T6	225	200	200	15.5
T6	250	146	146	17
T6	275	125	125	13.5
T6	285	95	97	23

* at test temperature for 180 minutes before testing
** at test temperature for 140 minutes before testing

Table 2a Ambient temperature

Temper	Test Collapse stress [MPa]	USFOS Collapse stress [MPa]	ABAQUS Collapse stress [MPa]
T6	211	219	207
T4	122	126	124

Table 2b Constant temperature rate

Temper	Stress level [MPa]	Heating rate [°C/min]	Test Critical temp. [°C]	USFOS Critical temp. [°C]	ABAQUS Critical temp. [°C]
T6	110	4.7	259	249	244
T4	75	4.6	286	285	282

Table 2c Constant temperature

Temper	Temperature [°C]	Heating rate [°C/min]	Test Collapse stress [MPa]	USFOS Collapse stress [MPa]	ABAQUS Collapse stress [MPa]
T6	204	11.2	131	155	128
T4	198	11.9	141	107	121