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EXPERIMENTAL ANALYSIS OF THE INFLUENCE OF CREEP ON FIRE-EXPOSED STEEL AND ALUMINIUM COLUMNS

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ABSTRACT

The paper presents test results of a study aiming to explore the influence of creep strain on reduction of the load-bearing capacity of fire-exposed steel and aluminium columns. The research focuses on the behaviour of columns made of steel grade S275JR and aluminium grade EN6082AW T6. Two types of high-temperature column tests were conducted in the study: constant-temperature capacity and creep tests. The temperature ranges for both capacity and creep tests are between 400-600°C for steel and 160-300°C for aluminium. The test results have shown that creep can reduce a steel column's load-bearing capacity, even at 400°C. The influence of creep on load-bearing capacity, without prolonged exposure to high-temperature, can be observed when the axial compressive load is above 87% of the steel column's axial load capacity. In the case of aluminium, creep starts to develop at approximately 160°C, at which the reduction in load bearing capacity is observed at loads above 88% of the column's axial load capacity.

Keywords: Steel, aluminium, fire, creep, column, S275JR, EN6082AWT6

1 INTRODUCTION

Experimental studies regarding the creep behaviour of steel and aluminium members in general are very scarce, due to the complexity of the experiments, which is necessary in order to properly capture the effects of creep in reducing load-bearing capacity. The influence of creep strain on the load capacity of metallic structures is a topic which has started to receive attention from scientists and researchers over the past decade. A major reason for the lack of previous research effort in this area is the fact that creep strain has long been considered as irrelevant to the response of metallic structures exposed to high temperature. Furthermore, the bulk of the fire tests performed by the scientific community have been conducted using standardized heating regimes that impose very rapid heating rates, generally above 20-25°C/min [1, 2], on a tested member; this ultimately leads to rapid member failure. With the introduction of natural fire curves into structural fire analysis for performance-based design it has become clear that it is not unusual for structures to be exposed to heating rates below 20°C/min, especially if the structure is exposed to slow-burning long-lived fires, or if it is covered with fire-protection material. Another possible reason for the paucity of

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creep-related research is the availability of implicit-creep stress-strain models, which are provided to practising engineers in codes of practice for various applications. The implicit-creep material model within the Eurocodes [3] for metallic structures are widely used, even beyond Europe. Several experimental studies conducted on steel beams [4, 5] have shown that the Eurocode 3 model has limitations in predicting deflection in cases where heating rates are lower than 10°C/min. The lack of detailed experimental data regarding creep development in contemporary European steel and aluminium grades, and very scarce member test studies, have resulted in the development of a research programme [6, 7] aiming to explore the influence of the time of high-temperature exposure on the overall load-bearing capacity of columns. The behaviour of columns in fire conditions is necessary [8, 9] since they represent the most vulnerable parts of a structure in terms of actual collapse. This study is part of a joint research programme (Croatian Science Foundation project no. UIP-2014-09-5711) conducted by the Universities of Split and Sheffield. Its three phases are: development of explicit creep models for alloys S275JR and EN6082AW T6 with the help of coupon stationary-creep tests, experimental tests on columns using constant-temperature tests, and the corresponding verification of these creep models. S275JR steel is widely used as a construction material in civil engineering across Europe, and the Aluminium alloy EN6082AW T6 is a structural alloy with minimum proof strength of 260 MPa, which is comparable to grade S275 steel.

2 METHODOLOGY AND TEST RESULTS

2.1 The heating and loading equipment

The column tests have been conducted at the University of Split. The heating arrangement used in this test study is based on induction heating. The induction equipment, which generates up to 35 kW of power, produces fields of high-frequency electrical currents in ferromagnetic metals located within its electric field, which cause them to heat rapidly. In the test setup used, these fields are generated in a cylindrical steel jacket surrounded by induction cables, as shown on Figure 1. The test setup and the steel/aluminium column specimens (HE140B and the section 220/170/15/9) are shown in this figure. A specimen placed inside the jacket is heated predominantly by radiation from the inner surface of the jacket, but also partially by the electrical currents which pass through the specimen (this is particularly true for steel specimens, which are ferromagnetic). With this kind of induction heating equipment it is possible to achieve very uniform heating in the column cross-sections, inducing negligible temperature variations between the columns’ upper and lower flanges.

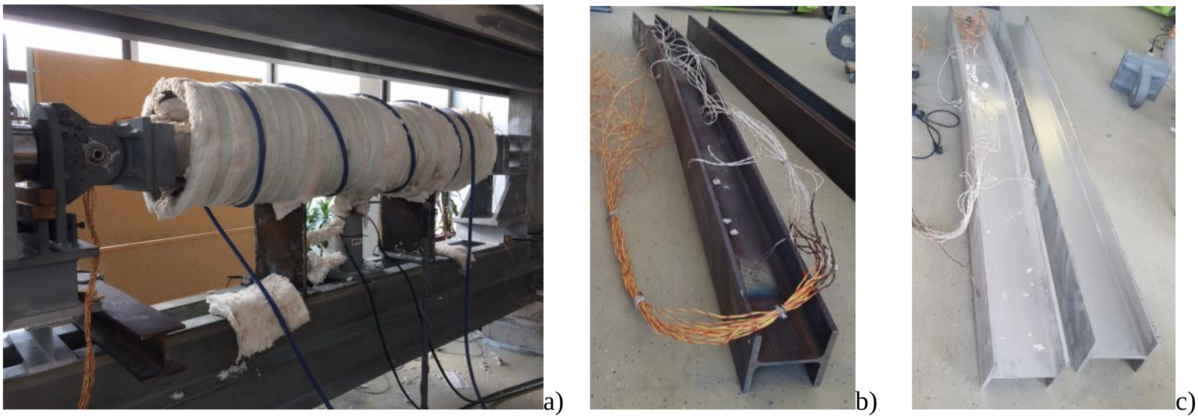
a) b) c)

Fig. 1. a) Test setup for aluminium columns; b) Steel column; c) aluminium column

There are some temperature variations over the column length, especially at their ends where slightly lower temperatures are generated. The two types of high-temperature column tests conducted in the study are constant-temperature capacity and creep tests. The temperature ranges for both test types were planned to be between 400-600°C for steel and 160-300°C for aluminium. These were based on previous coupon test results, which suggested that within these temperature ranges both metals exhibit very rapid strength reduction. Therefore, it was impractical to conduct tests beyond 600°C for steel [6] or 300°C for aluminium [7], since above these temperature thresholds more than 70% of the materials' strengths are lost, according to these coupon studies.

The loading equipment comprised two hydraulic rams capable of applying axial force up to 1500 kN (horizontal ram) and 300 kN (vertical ram). Measurement of axial end-displacements and transverse mid-span displacement was conducted using LVDTs in the appropriate positions. As can be seen from Figure 1, the column is transversally loaded with a relatively small force about its weak axis.

2.2 Capacity tests

Capacity tests were conducted in order to determine a column's axial load capacity at a prescribed constant temperature with a constant transverse force. The column was heated to the prescribed temperature, loaded with the constant lateral force, and subsequently loaded with a controlled increasing axial compressive force until column failure. Capacity tests were conducted at temperature levels of 400-500-600°C for steel and at 160-220-260°C for aluminium.

2.3 Creep tests

The creep tests were conducted by firstly heating the column to a prescribed temperature, and then loading it with the constant lateral force. The final step was then to add a constant axial compressive force, defined as a fraction of the axial load capacity at the prescribed temperature level. The column was then maintained at the prescribed temperature and load level until a gradual column failure due to creep occurred. These constant-temperature creep tests were also performed at temperature levels of 400-500-600°C for steel and 160-220-260°C for aluminium.

2.4 Temperature measurements

Temperature measurements were conducted at thirteen different points, with a total of five cross-sections containing either two or three discrete measuring points. This unusually large number of measuring points is necessary in order to properly record the temperature fields during the experiment. The heating rate of the induction equipment was monitored using two thermocouples, one placed on the inner surface of the jacket and the second placed on the web of the specimen at mid-span. Figure 2 shows the temperature measuring points on the steel specimen. The distribution of the measuring points for temperature in case of aluminium columns is identical to that for steel columns. Figure 3 presents the temperature measurements at various points for the steel column experiments conducted at 400°C.

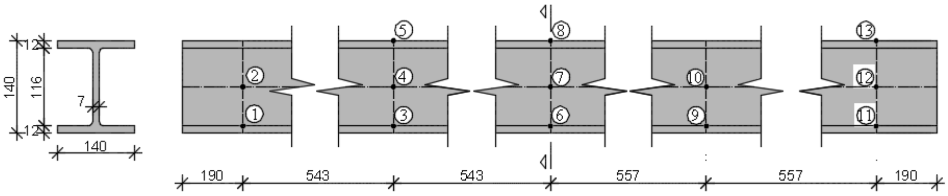

Fig. 2. Measuring points for temperature – steel columns

It can be seen from Figure 3 that the column ends are heated to slightly lower temperatures than those at mid-span. This difference varies with the level of the target temperature, and can be higher for the 500°C and 600°C target temperatures than that for 400°C. In both capacity and creep tests thermal expansion of the column was left unrestrained before the application of the external load.

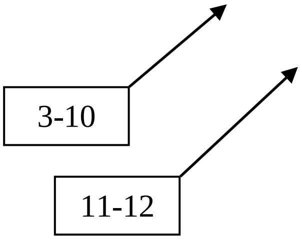

Fig. 3. Temperature measurements – steel creep test at 400˘C

2.5 The influence of friction

It is well known that, during column compressive tests, the influence of friction can be substantial on the measured load-bearing capacity [9]. Therefore, it is necessary to give specific consideration to reducing this unavoidable effect. In the research presented here the friction is reduced by using two strategies. The first is general, and includes lubrication of the pins as well as the supporting plates. The second is the use of a lubricated cylindrical thin steel shim between the pin and its bearing, which effectively increases the lubricated surface. Column tests at normal temperature with and without the applied lubrication strategy have shown that the reduction of the friction effect where the column's critical force is about 44%, indicating that this lubrication strategy is effective.

2.6 Test results

The test study presented in this paper will eventually include tests on a total of 17 steel and 36 aluminium columns. Tables 1 and 2 present the test parameters of the capacity tests conducted so far. Tables 3 and 4 present the test parameters of the creep tests at 400°C (steel) and 160°C (aluminium).

Table 1. Capacity test results for steel

Temperature (°C)	Axial load (kN)	Vertical load (kN)
20	478.0	46.0
400	560.0	37.0
500	530.0	30.0
600	376.0	16.0

Table 2. Capacity test results for aluminium

Temperature (°C)	Axial load (kN)	Vertical load (kN)
20	656.0	60.0
160	488.0	48.0
210	624.0	37.7
260	402.0	26.0

Table 3. Results of steel creep tests – 400°C

Test No.	Axial load (kN)	Vertical load (kN)	Failure time (min)	Load ratio (%)
1	488.0	37.0	37.8	87
2	518.0	37.0	7.5	93
3	535.0	37.0	6.1	96

Table 4. Results of aluminium creep tests – 160°C

Test No.	Axial load (kN)	Vertical load (kN)	Failure time (min)	Load ratio (%)
1	427.0	48.0	151.7	88
2	457.5	48.0	25.9	94
3	475.8	48.0	3.6	98

Figure 4 presents creep test results for axial force and displacement of aluminium columns at 160°C (Tests No. 2&3). The capacity and creep tests are generally terminated when the axial displacement begins to indicate run-away behaviour.

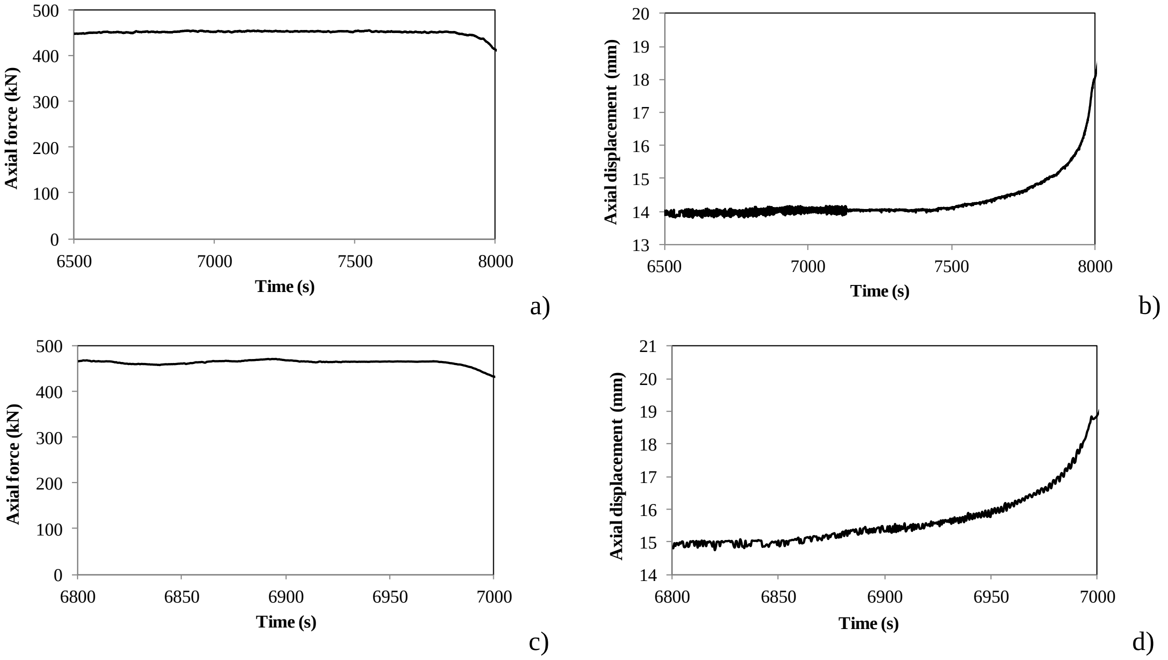

Fig. 4. Creep test results of aluminium at 160°C: a)-b) - Test No.2 ; c)-d) – Test No. 3

3 DISCUSSION OF THE RESULTS

It can be seen from the creep tests for steel that at 400°C columns have very low short-term creep resistance for axial loads higher than 90% of the column's axial load capacity. However, for load ratios below 90% the column's creep resistance starts to increase rapidly. A similar observation can be made for the presented aluminium creep tests. This suggests that, at any discrete temperature level, a range of load ratio exists within which creep rapidly reduces the column's axial load capacity. This short-term creep resistance could be a problem for high-rise structures where lower-storey columns are predominately loaded by axial compressive force. It is important to note that even at 400°C (for steel) and 160°C (for aluminium) the results have shown that the columns are sensitive to prolonged high-temperature exposure, indicating that these temperature levels should be treated with care in structural design procedures. For steel, 400°C is not generally considered as a critical temperature, since at this temperature level there is a negligible reduction in yield strength for European low-carbon steels. However, when considering the period of time within which steel is exposed to high temperature, it is obvious that a reduction of a column's load-bearing capacity is possible, even at 400˘C. This suggests that a new way of thinking on the ultimate load bearing capacity of columns in fire conditions is necessary, including the period of time for which they are exposed to high temperatures. This may need consideration in the future development of building codes.

4 CONCLUSIONS

The column tests conducted so far suggest that there is a connection between the critical temperature interval for creep development, obtained in previous coupon studies, and the results from this column study, in terms of failure due to creep. Very low short-term creep resistance can be observed for the columns under loads which are higher than approximately 90% of their axial load capacity at 400°C (steel) and 160°C (aluminium). Further studies will include analysis of the column creep behaviour at temperature levels up to 600°C in the case of steel and 300°C in case of aluminium. The experimental study will be supported by numerical analysis of the tests in order to appropriately track the reduction of load capacity due to creep.

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