Thermal and axial compression behaviour of full-scale concrete-filled steel-tube columns (RCFST) exposed to fire: Experimental Study

M. Acito
Politecnico di Milano, Milano, Italy

ABSTRACT: This paper presents experimental results of fire and compression tests performed on full-scale fire-exposed Reinforced Concrete-Filled Steel Tubes (RCFST) and Reinforced Concrete (RC) short columns (outer diameter 457 mm and length 1600 mm). In the paper, full details about the test procedure, thermal field, load-displacement curves and main remarks about the results are given. In particular, this research work presents the results of five tests for thermal field measurements, that consider four specimens heated in a gas furnace in standard fire conditions (ISO 834) and one specimen heated in an electric furnace in non-standard conditions. Also, the study presents the results of six axial compressive tests. In association to this work, three other papers are presented. In the first companion paper, the results of standard thermal tests are discussed and a numerical-experimental comparison is proposed. In the second companion paper, the results of residual compression tests are discussed and an analytical-experimental comparison is proposed. In the third companion paper, the results of non-standard thermal test and a "hot" condition compression test are discussed. Also, a numerical-experimental and an analytical-experimental comparisons are proposed for non-standard thermal tests and "hot" condition compression test respectively.

1 INTRODUCTION

The use of Concrete-Filled Steel Tubes, with or without ordinary longitudinal reinforcement (indicated with the acronyms CFST/RCFST, where C means "plain" or "unreinforced concrete", and RC means "reinforced concrete"), is very common in many countries like the USA, China and Australia, while the use of CFST and RCFST columns in Italy is rather recent. Although limited in number, recent examples of two hospitals in Vimercate and Bergamo, both close to Milan, could be cited. Many studies have shown the advantages offered by CFST/RCFST columns in terms of higher load-bearing capacity, stiffness and ductility, compared to traditional steel or RC columns (see for instance: J. P. Schneider (1988), Zhi-wu Yu et al. (2007) and J. Liu, X. Zhou (2010)). In addition to their structural advantages, CFST/RCFST columns bring in further significant technological advantages, due to the possibility of using the steel tubes as a structural formwork aimed to support the loads during the construction phase. The growing interest for CFST/RCFST columns and the concern for their behaviour under exceptional events such as fire were the starting point of several numerical/analytical and experimental studies aimed at characterizing the thermo-mechanical behaviour of these structural members, on the basis of the extensive knowledge of concrete and steel behaviour at high temperature and in fire.

Among the various contributions, those by Lie (1994), on circular and rectangular columns should be mentioned. Of great interest are also the works by M. Fontana et al. (2017) on CSFT columns filled with solid steel core subjected to fire. As for the post-fire phase, a contribution on the residual load bearing capacity of RCFST is given by Liu et al. (2014), where experimental and numerical studies into the structural behaviour of reinforced concrete filled steel tubes circular columns after exposure to standard fire conditions, were presented. In the work by Rush et al. (2015), the post-fire residual compression tests on unprotected and protected CFS columns along with control tests on six unheated sections were presented. In that work, the tests confirmed that as the maximum exposed temperature within the cross-section increases, the residual strength capacity, ductility and axial–flexural stiffness decrease. In all the aforementioned works on the behaviour of concrete-filled steel tubes in fire, a variety of values for the depth/diameter ratio (L/de) and for the size were considered, but the experimental results on full-scale columns were scanty indeed. Therefore, the experimental study presented in this paper is one of the few examples concerning the testing of circular columns in fire (with diameter close to 500 mm). In this work, tests in compression were carried out at high temperature and past a thermal cycle (in the following indicated as “hot” and “residual tests”, respectively), and the thermal field was monitored under the standard fire (ISO 834 (1975)), as well as under a much less severe heating (in terms of heating rate), obtained by an electric furnace. Whereas the “hot” test give information about the capability of the columns to resist a major fire event, the “residual tests” are instrumental in evaluating the bearing capacity of the column in post-fire condition, useful in order to decide whether and how to re-use the fire-damaged structure (as it is or after some repairing).

The availability of such experimental data was important in order to perform a comparison with numerical results obtained by thermal analysis, but also to use them for the analytical fire standard code safety checks of the columns. For the discussion of the experimental results and the comparison between numerical and experimental findings see the companion paper by Acito & Lavermicocca (2019), where for a comparison of measured and numerical thermal analysis field results, the usual relationships for the temperature-dependent material properties (such those of the Eurocodes EC2 (2004) and EC4 (2005)), are considered.

Similarly, the availability of such experimental data on axial compressive bearing capacity of the columns, both in “hot” condition and in residual condition, allowed some important comparisons with simplified analytical estimations of the axial compressive bearing capacity of the columns, based on the classical models of literature, suggested both for the heating phase and for the post-fire condition. Specifically, for the heating phase comparisons, the EC2 and EC4, Li and Purkiss’s (2005) material models, Lie’s (1994) material models, Yin and Li’s et al. (2006) material models for concrete and steel at elevated temperatures, were employed.

Whereas, for the post-fire phase comparisons, both Chang’s concrete model (2006) (based on the TSAI’s model (1998), and modified EC2 and EC4 concrete models, suggested by the author, were employed. For the discussion of the compression tests and the comparison between analytical and experimental findings see the companion paper of Acito&Jain (2019), while the discussion of the “hot” condition compression test and the comparison between analytical and experimental findings is given in the companion paper by Acito&Chesi (2019). In this paper presents all the details about the experimental program and the obtained results.

2 EXPERIMENTAL PROGRAM AND GEOMETRY OF THE SPECIMENS

2.1 *Experimental program*

As previously mentioned, the experimental study is focused on full-scale RCFST specimens with a diameter close to 500 mm (outer diameter 457 mm and length 1600 mm, Fig. 1). The length was limited to 3-times the diameter, because of obvious handling problems, but also because in this way the specimens can be assumed as representative of the structural behaviour (axial compressive load) of the actual columns (length 3,5 m), used in the (braced frames) structure of the building. All specimens (except Spec. IV) consist of a steel cage (bars and ties) placed inside a steel tube, which is filled with NSC (normal strength concrete).

a) b)

Figure 1. Bergamo Hospital site: a) steel cages with Chromel-Alumel thermocouples; b) Specimens Cast

In the original building, RCFST columns were preferred to CSFT columns (no reinforcement) because of their better performance. In fact, limiting the attention to fire resistance, internal reinforcement plays a sizable role since part of the load is transferred from the steel tube to the concrete and to the reinforcing bars, as soon as the steel tube is heated and rapidly loses its load-bearing capacity. Moreover, the load redistribution from the steel tube to the core, combined with the decreasing lateral confinement provided by the steel tube, tends to make filled columns similar to ordinary unconfined R/C columns, where the placement of internal ties and bars is mandatory. The thermal field was measured by using a set of embedded Chromel-Alumel thermocouples (covered with protection sheaths, see Figs. 1, 2).

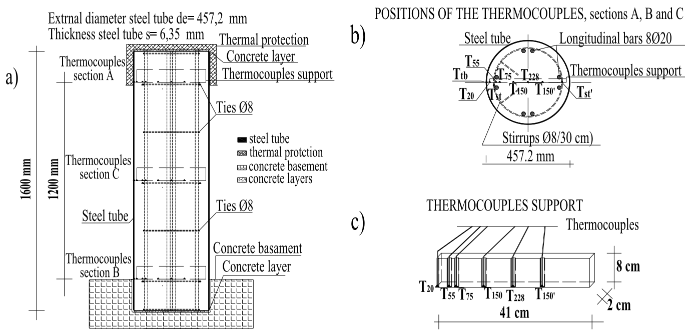


Figure 2. Geometry of the specimens and positions of the thermocouples (three levels: A, C and B, from top to bottom).

Five specimens were cast, one without the steel tube (Spec. IV) and four with the steel tube (Spec. I, II, III and V); however, all were identical in terms of concrete geometry and reinforcement. For the residual tests, the heating process was performed in accordance with the standard temperature-time curve ISO 834. The four residual tests were carried out after heating the specimens in the gas-fuelled furnace (Fig. 3) of the Centro Sperimentale Italiano – Italian Test Center (CSI, Milan), while, for the non-standard heating process, a single "hot" test, the split-type electric furnace of the Materials Testing Laboratory (LPM) of the Politecnico di Milano, was used. As already mentioned, the fire tests performed on columns I, II, III and IV were carried out at CSI by partially exposing the lateral surface to the fire (the top and bottom 200 mm-long butts were insulated, while the 1200 mm-long central part was directly exposed to the fire, Figs. 2 and 3 a). In this way, the experimental data collected about the distribution of the measured temperatures on the section C, as caused by a quasi-uniform directly exposition to the fire on the 1200 mm-long central part of the specimens, can be considered. While, along with the experimental data collected about the distribution of the measured temperatures on the sections A and B, the effects of the boundary condition have been measured. After cooling down to room temperature (Fig. 3 b), Specimens I-IV were brought to the LPM, where the tests in compression were carried out (Fig. 4). (So, Tests 1-4 were carried out after exposing the unloaded Specimens I-IV to the standard fire (temperature-time curve ISO 834, fire duration 180 minutes)). Table 1 summarizes the six tests performed on the five specimens. Again at LPM, Specimen V was tested both in ambient condition (Test 5) and at high temperature (Test 6). In Test 5, Specimen V was firstly loaded to 2500 kN and then unloaded (Fig. 5). The purpose of this test was to gather some information about the behaviour of the column in ambient conditions and prior to the heat treatment. Specimen V was the only specimen tested at high temperature in the electric furnace (Test 6, Figs. 6a,b). The load was applied before the heating process and was kept constant throughout the test at high temperature (N_{Ed}=2200 kN – axial load columns, evaluated by structural analysis for the design fire ultimate load combinations). The split furnace and its electric panels were designed in such a way that they could be placed between the platens of a hydraulic press (capacity 5000 kN). Since only the central part of each specimen was heated (heated length 1200 mm; total length 1600 mm), the press platens were 200 mm apart from the heated zone; however, in order to avoid any overheating of the platens, proper insulation was used (Fig. 6) and a thermal camera monitored the temperature of the platens. Obviously, this test cannot be assumed as having general value because of its reduced thermal power (heating rate [ΔT/Δt] average=4-5°C/min), hence the electric furnace could not reproduce a standard fire.

Table 1: Synthesis of the experimental program.

Test No	Spec. No	Spec. Type	Test Cond. (1)	Heating (2)	TMP/ LDC (3)	Max. Load test [kN] (5)	De-tails (5)
1	I	RCFST	RES.	Fast	yes/yes	3500^x	Δ
2	II	RCFST	RES.	Fast	yes/yes	5000*	ΔΔ
3	III	RCFST	RES.	Fast	yes/yes	5000*	ΔΔ
4	IV	RC	RES.	Fast	yes/yes	2500^	ΔΔ*
5	V	RCFST	AMB.	-	no/yes	2500**	ΔΔΔ
6	V	RCFST	HOT	Slow	yes/yes	4300^§§	ΔΔΔΔ

(1) RES = residual test–standard-fire duration of 180 minutes; "HOT" = test at high temperature – heating for 5 hours; AMB. = test in ambient conditions

(2) Fast (stn) = standard fire (ISO 834); Slow = 4-5°C/minute

(3) TMP = monitoring of the temperature (thermal mapping) ; LDC = measuring of the load-displacement curve

(4)* = test limited 92 % of the expected residual capacity; ** = test limited to 1/4 of the expected ultimate load in ambient conditions; ^ = test to failure; §§ =slow heating for 310 minutes (equivalent to a standard-fire duration of 120 minutes).

(5)***=preloading during the heating process equal to the axial load, evaluated by structural analysis for the design fire ultim. load comb..

Δ Residual conditions with tube removed prior to testing

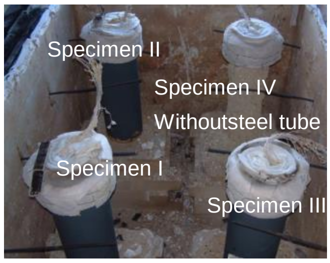
ΔΔ Residual conditions

ΔΔ* Residual conditions without steel tube

ΔΔΔ Ambient conditions

ΔΔΔΔ Hot conditions, after 5 hours at 2200 kN ***

a)



b)

Figure 3. CSI Fire Tests: a) Specimens in the furnace before heating standard process; b) Specimens in the furnace after heating standard process

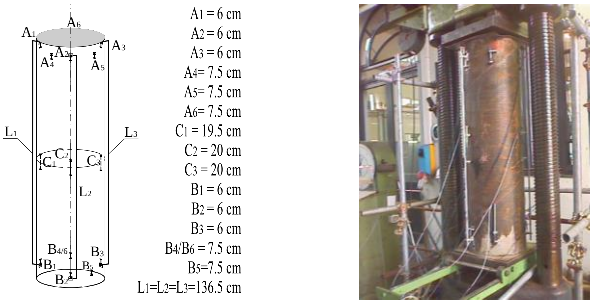
a) (test 1)

b) (test 2)

c) (test 3)

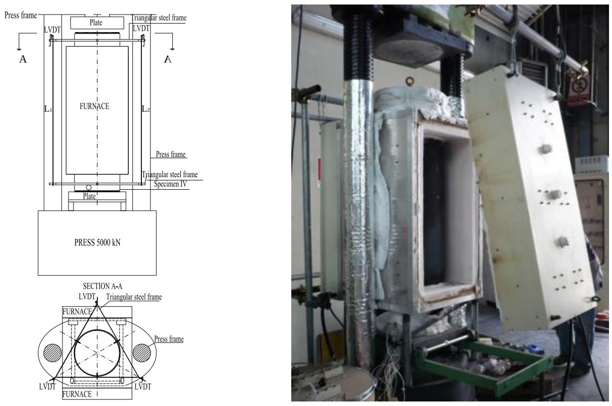
d) (test 4)

Figure 4. Compression tests at LPM of Politecnico di Milano: a) Specimen I; b) Specimen II; c) Specimen III; d) Specimen IV.



a) b)

Figure 5. Compression test at LPM of Politecnico di Milano: a) locations of the LVDTs; b) Specimen V (test 5) between the press platens.



a) b)

Figure 6. Specimen V: a) test setup for loading at high temperature with the positions of the LVDTs; b) test setup after Test 6(b).

Therefore, this tests cannot be assumed as having general value, but only being a rough approximation of the behaviour of the actual columns subjected to axial load during the heating, evaluated in the design fire ultimate load combination after 120 min of standard fire exposure. After 5-hours at high temperature, the load was decreased to 500 kN and then was increased up to the collapse of the specimen (4300 kN). Spec. V was unloaded after 5 hours, and then re-loaded up to failure following a force-controlled procedure, as in all other tests. Fig. 6 b) shows the furnace after Test 6 (Spec. 5). In the companion paper (Acito&Chesi (SEMC2019)), the results of non-standard thermal test and a “hot” condition compression test are discussed.

3 INSTRUMENTATION, SPECIMENS REINFORCEMENT, MATERIALS PROPERTIES AND CONCRETE CASTING

3.1 *Instrumentation*

The thermal field was monitored in three “reference” sections (Figure 2 a,b). These three sections were located at mid-span (Section C) and at the ends of the heated zone (Sections A and B at ±600 mm from the mid-span section). Each section was instrumented with 9 thermocouples as shown in Figure 2b, where T_{tb}=thermocouple attached to the steel tube; Tst= thermocouple aligned with the reinforcement ties/stirrups; Ti= thermocouple located at a prescribed distance from the external surface of the specimen, with the subscript indicating the distance (e.g. T20 indicates a thermocouple located 20 mm from the external surface of the tube in Specimens I, II, III and V, and from the surface of the concrete in Specimen IV); the apex ’ indicates the thermocouples located in symmetrical positions, like Tst' with respect to Tst, and T150’, with respect to T150.

In order to keep the thermocouples in place during concrete casting, the thermocouples were glued to special precast concrete prisms (Fig. 2 c), which were diametrically placed in Sections A, B and C, and fixed to the reinforcement cage. Prisms size was: length =417 mm; depth =80 mm; width=20 mm. Each prism had a number of lateral grooves, for the placement of the thermocouples (Figs. 1 and 2).

3.2 *Specimens and material properties*

The same steel types used in the actual columns were used in the specimens (tubes and reinforcement), see Table 2. Each specimen contains 8 longitudinal high-bond bars (diameter ϕ=20 mm), and evenly-spaced circular ties (diameterϕ=8 mm, spacing=300 mm; Figures 1 and 2 a,b). The external diameter and the thickness of the steel tube are 457 mm (18”) and 6.35 mm, respectively. The mean strength (of 6 150 mm-cubes Specimens) of the concrete R_{cm}, at 28 days, was 45 MPa (f_{cm}=37 MPa), and the mass per unit volume turned out to be 2300 kg/m^3.

Table 2. Mechanical properties of the steel types used in the specimens.

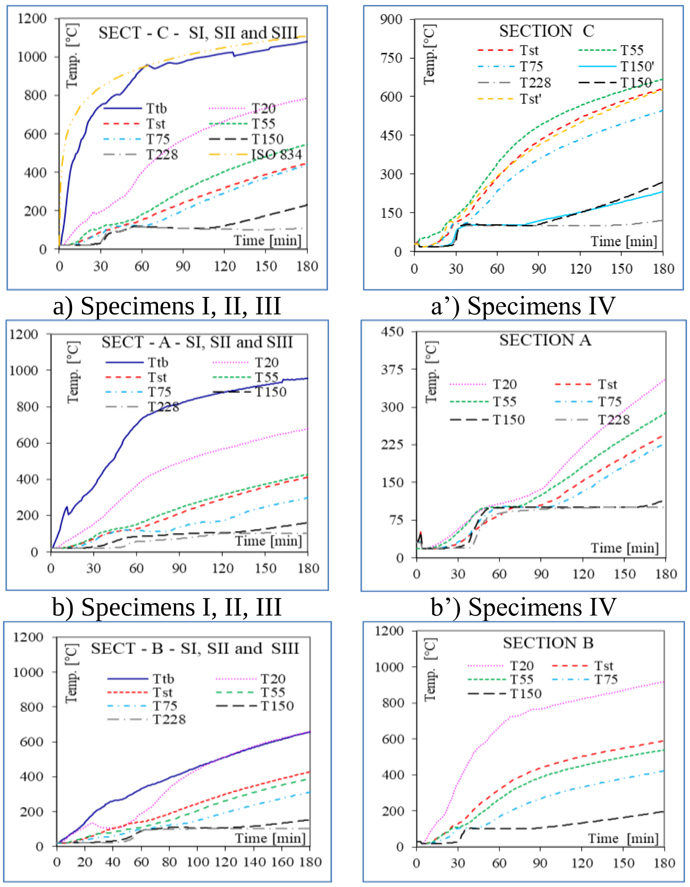
Concrete	Steel tubes	Reinforcement steel
R_{cm}=45 MPa	Type Fe430 B	Type FeB44k
f_{cm}=0.83 R_{cm}	(f_{yk}=275 MPa)	(f_{yk}=430 MPa)
f_{cm}=37 MPa	(f_{ym}=298 MPa)	(f_{ym}=452 MPa)

From the geometric sectional dimensions of the columns, it can be evaluated: A_s/A_c=0.0163 and A_{tb}/A_c=0.0571. In which: A_s=25.12 cm^2, is the steel bars cross-sectional area; A_c=1544 cm^2, is the concrete core cross-sectional area; A_{tb}=88.21 cm^2, is the steel tube cross-sectional area. The specimens were cast at the building site of the new hospital in Bergamo (Figs. 1a, 2).

4 THERMAL MAPPING DURING THE STANDARD-FIRE EXPOSURE

4.1 *Heating process and results of the fire exposure*

The temperature-versus-time plots of the confined specimens measured on the sections C of the three specimens are very similar. So in Fig. 7 a) a mean of the measured values is reported. Similar considerations for the temperature-versus-time measurements for sections A and B allowed to assume each value of the temperature as the mean of the measured values recorded by nominally-identical thermocouples of the Specimens I, II and III (Figs. 7 b and 7c). So, the temperature-versus time plots of the confined specimens shown in Figs. 7 a, 7 b, 7c (Sections C, A and B, respectively) have been obtained as the mean of the values measured in the nominally-identical thermocouples of the Specimens I, II and III. In Fig. 7a’), b’) and c’), instead, the measured temperature-versus-time plots recorded by the thermocouples placed in sections C, A e B of the Specimen IV, are shown.



a) Specimens I, II, III a’) Specimens IV

b) Specimens I, II, III b’) Specimens IV

c) Specimens I, II, III c’) Specimens IV

Figure 7. Plots of the mean values of the measured temperatures in various locations: a) section C; b) section A; c) section B.

5 TESTS IN COMPRESSION

5.1 Tests Setup

All compression tests were performed at the Politecnico di Milano, using a 5000 kN hydraulic press. The specimens were capped by means of a 20 mm-thick mortar layer, in order to have the load directly transferred from the press platens to the concrete core. The data-acquisition system consisted of a Spider 8 Data Recorder (by HBM), connected to a set of LVDTs. The following parameters were measured:

1. the deformation of the concrete core, monitored by means of three LVDTs at 120°, having a base-length roughly equal to the total length of each specimen, capping excluded (L_i in Fig. 5 a,b and in Fig. 4 a-d: L_i=86 % of the total length);
2. the deformation of the steel tube, monitored by means of three LVDTs placed across the mid-span section of each specimen (C_i in Fig. 5 a,b and in Fig. 4 b,c);
3. the local slip between the steel tube and the concrete core, monitored by means of three LVDTs placed close to the end sections of each specimen (A_i and B_i in Figure 5 a,b and in Fig. 4b,c); in the same zones, the longitudinal deformation of the steel tube was measured as well.

Each specimen was firstly loaded in compression up to 20-25% of the design load in fire (500 kN) and then unloaded; after this “stabilizing” cycle, the specimen was loaded up to failure (Specimen I, Table 1) or up to a load very close to the one expected at failure (Specimens II and III, Table 1).

Figure 5 a) refers to the location of the LVDTs in Specimens II (test 2), III (test 3), and V (test 5). For the specimens I (test 1), IV (test 4) and V (test 6), the deformation of concrete was monitored by means of the only L_i LVDTs at 120° (figs 4 a, d and 6).

5.2 Experimental Results

The mean load-strain curves are reported in Fig. 8, with reference to the strain in the concrete (LVDTs $L_{i=1,2,3}$).

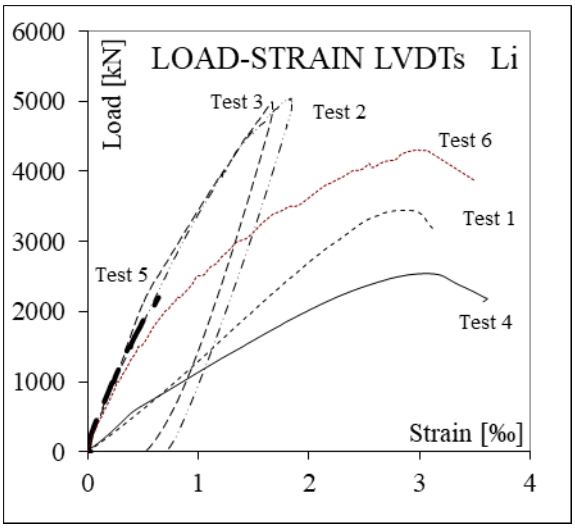


Figure 8. Load-strain curves (LVDTs Li).

In order to understand Fig. 8, let us recall some of specimens’ properties (from the strongest to the weakest behaviour, see also Table 1):

- Test 1 (Specimen I) had the tube removed after the heating phase and prior to loading (residual test);
- Tests 2 (Specimen II) and Test 3 (Specimen III) were carried out on tube-confined and nominally identical specimens (residual tests);

- Test 4 (Specimen IV, without steel tube) was carried out on the unconfined specimen (residual test);
- Test 5 was limited to the elastic behaviour of Specimen V;
- Test 6 (Specimen V) was carried out on a tube-confined specimen preloaded during the heating phase (“hot” test).

6 CONCLUSIONS

The experimental study presented in this paper is one of the few examples concerning the testing of circular columns in fire (diameter close to 500 mm). In this work, tests in compression were carried out at high temperature and past a thermal cycle (“hot” and “residual tests”), and the thermal field was monitored under the standard fire (ISO 834-1975), as well as under a much less severe heating (in terms of heating rate).

The plots of temperatures measured at various locations show the important role played by the steel tube with reference to the concrete spalling issue and to the reduction of the maximum temperatures reached for the same fire exposure duration.

The load-strain curves show the important role played by the steel tube with reference to the initial slope of the load-displacement curves.

For the discussion of the experimental results and numerical/analytical comparison see the companion papers by Acito & Lavermicocca (2019), Acito&Jain (2019) and Acito&Chesi (2019). In the first companion paper, the results of standard thermal tests are discussed and a numerical-experimental comparison is proposed. In the second companion paper, the results of residual compression tests are discussed and an analytical-experimental comparison is proposed. In the third companion paper, the results of non-standard thermal test and a “hot” condition compression test are discussed. Also, a numerical-experimental and an analytical-experimental comparisons are proposed for non-standard thermal tests and “hot” condition compression test respectively.

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