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Methodology for brick/mortar interface strength characterization at high temperature

Jérôme Brulin¹, Eric Blond², Emmanuel de Bilbao³, Amna Rekik², Matthieu Landreau⁴,
Alain Gasser², Yannick Colleville²

¹ *Saint-Gobain Research Provence, 550 avenue A. Jauffret, 84306 Cavaillon, France*

² *Univ. Orléans, Univ. Tours, INSA-CVL, LaMé, 8 rue L. de Vinci, 45072 Orléans, France*

³ *CEMHTI (CNRS, UPR3079), 1D avenue de la Recherche Scientifique, 45072 Orléans, France*

⁴ *ArcelorMittal France, 3031 rue du Comte Jean, CS 52508, 59381 Dunkerque Cedex 1, France*

jerome.brulin@saint-gobain.com, eric.blond@univ-orleans.fr, emmanuel.debilbao@univ-orleans.fr, amna.rekik@univ-orleans.fr, matthieu.landreau@arcelormittal.com, alain.gasser@univ-orleans.fr, yannick.colleville@univ-orleans.fr

Abstract:

The interface between bricks and mortar is often the weakest part of masonry structures. For refractory linings, the interface strength must be measured at high temperature. Adapted slant shear tests and a new dedicated tensile test set up are proposed here for this purpose. To test the ability of the proposed method, it was applied on two representative brick/mortar couples from room temperature up to 1450°C. Slant shear tests were conducted to measure ultimate compression and shear stresses and to identify temperature dependent parameters of the Mohr-Coulomb failure criterion. Tensile tests were performed to identify the tensile cut-off. Depending on the brick/mortar couples, the failure can appear at the interface or in the mortar. Cohesion and tensile strength decrease sharply over 900°C.

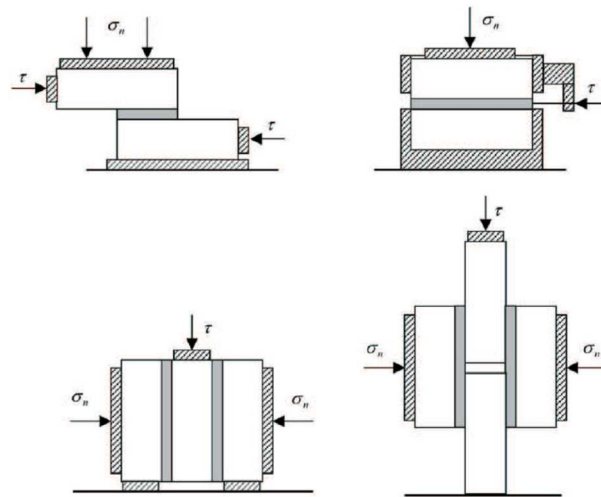
Keywords: refractory materials, high temperature, tensile test, slant shear test, brick/mortar interface strength, Mohr-Coulomb criterion.

1. Introduction

High temperature industries (i.e. steel or gas industries, glass making, ...) require structures made of many different linings, from inside to outside: a working lining in contact with hot products, a safety lining, an insulating lining, and an outer steel shell. Parts of these linings consist of refractory masonries, with or without mortar. Masonry structure modelling is studied extensively owing to its wide application in many other fields such as civil engineering or cultural heritage renovation [1-3 for example].

Quasi-brittle materials, such as concrete, mortar, ceramics or refractory materials, generally fail due to progressive crack growth. This mechanical behaviour is usually explained by the heterogeneity of the material due to the presence of different phases and material flaws. The modelling of the thermo-mechanical behaviour of refractory materials presents many difficulties in common with concrete and geo-materials (e.g. asymmetric damage behaviour, interaction with the environment) added to particular effects due to service temperature in the range 800°C – 1600°C such as the appearance of asymmetric creep behaviour [4]. However, in the case of masonries, cracks appear most of the time at the brick/mortar interface because it is generally the weakest link of the assembly [5]. This observation, associated with the quasi-

51 brittle behaviour of mortar, leads to the definition of a discrete damage kinetic law for
52 masonry. This assumption is at the origin of the development of a homogeneous equivalent
53 material with behaviour depending on the “joint state” [6], i.e. perfect interface or broken
54 joint. This approach was first used in the particular case of mortarless refractory masonries,
55 to model the bottom working lining of a steel ladle with an adapted joint state definition: open
56 or closed [7]. In view of the promising results obtained, the approach was refined and
57 experimentally validated at room temperature by Nguyen *et al.* [8], confirming the ability of
58 a model based on the homogenisation of the masonry combined with a “joint state concept”
59 to reproduce the whole behaviour of a wall. An extension of this joint state concept, initially
60 developed for 2D masonries at room temperature, to 3D refractory masonries with
61 temperature dependent behaviour was then proposed by Landreau *et al.* [9].
62 In refractory applications, the high thermal gradient across the wall induces tensile stresses on
63 the cold face. Moreover, the thermal expansion is never totally free in the whole structure and
64 it can locally induce bending of the refractory lining, and thus tensile stresses in one part of
65 the structure. As a result, refractory brick/mortar interfaces can fail under tensile load and
66 under compression - shear load. It is therefore necessary to characterize the refractory
67 brick/mortar interface with respect to these solicitations from room temperature up to 1500°C.
68 The combined compression/shear load in masonries is widely investigated in civil engineering
69 with the classical shear wall test [10] and deep-beam test [1]. At a local scale, dedicated
70 devices have been developed to test brick/mortar interfaces. Figure 1 shows the main
71 principles used to apply normal and tangential controlled stresses. Tests on two bricks pasted
72 by one mortar joint as on the top right of Figure 1 [11, 12] or on three bricks pasted by two
73 mortar joints as on the bottom left [13, 14] are the most frequently used. It is worth mentioning
74 that the European standard corresponds to the test presented on the bottom left of Figure 1
75 [15]. Some authors have proposed more complicated tests on larger structures to ensure stress
76 homogeneity [16]. However, to the best of our knowledge, in every case available in the
77 literature, these tests were performed at room temperature.
78



79
80 Figure 1: Set of devices for shear tests [11]
81

82 On the other hand, although tensile fracture has also been considered in civil engineering [17-
83 19], it has been less studied in the framework of brick/mortar interfaces [20]. Tensile fracture
84 is increasingly studied in refractory materials with crack propagation tests such as the wedge
85 splitting test for example [21]. The bending test is the most popular mechanical test at high
86 temperature since it is the easiest to perform in the range 800°C – 1600°C even if it is difficult
87 to use the experimental data properly [22, 23]. However, this test is not fully suitable to study

88 brick/mortar interface strength because the stress field is not homogeneous in the section of
89 the sample, as is also the case in the wedge splitting test [21].
90 Different test methods can be used to apply a tensile stress through a section of a specimen.
91 Devices and set-ups have been developed to perform tensile tests on monolithic refractory
92 samples at high temperature [24, 25]. They require sample preparation to ensure clamping and
93 alignment which might damage the samples (made of an assembly of bricks and joints). On
94 the other hand, Almeida *et al.* [26] presented a brief summary of methods to characterize the
95 tensile strength of joints based on direct tensile tests, crossed brick couplets and bending tests.
96 The direct tensile test is the best method to study the tensile behaviour but some technical
97 problems were pointed out by van Mier and van Vliet [27] such as the alignment of the loading
98 chain including the specimen, the preparation of the specimen itself and the gripping. Different
99 specially designed clamping devices have therefore been developed to be used at room
100 temperature but all of them are too bulky to be placed in a furnace. Moreover, the materials
101 used cannot withstand high temperature. Crossed brick couplets and bending devices present
102 the same problem.
103 Other experimental set-ups exist in the refractory community, but they were designed to
104 identify complex tensile behaviour relationships taking into account damage [28] or creep [24]
105 at high temperature and do not seem to be well adapted to characterize the brick/mortar
106 interface strength.
107 Finally, whatever the fracture mode investigated, to the authors' knowledge, there is not any
108 complete set of devices to characterize the high temperature strength of interfaces. Thus, the
109 purpose of this paper is to present two specially designed devices to identify the brick/mortar
110 interface strength at high temperature: a slant shear test and a dedicated tensile test.
111 A simple model of the interface behaviour is proposed, namely an interface failure criterion
112 based on a Mohr-Coulomb yield function (for compression and shear) and a tensile cut-off.
113 Its parameters can be determined using the previously developed tests.
114 To illustrate the ability of the devices developed, two couples of bricks and mortars were
115 considered, covering a large temperature range. The use of the experimental results to identify
116 the interface failure criterion is also described.

117
118
119

120 2. Interface failure criterion

121

122 The shear strength of the brick/mortar interface typically depends on the normal stress applied
123 to the interface. This friction type behaviour is classically described by the Mohr-Coulomb
124 yield function:

125

$$126 f(\tau, \sigma_n, \Phi) = |\tau| - c + \sigma_n \tan \Phi \quad (1)$$

127

128 where τ is the shear stress, σ_n is the normal stress (negative in compression), c is the cohesion
129 of the material and ϕ the internal angle of friction (Figure 2). Determining cohesion and the
130 internal friction angle requires the measurement of normal and shear stresses until failure.

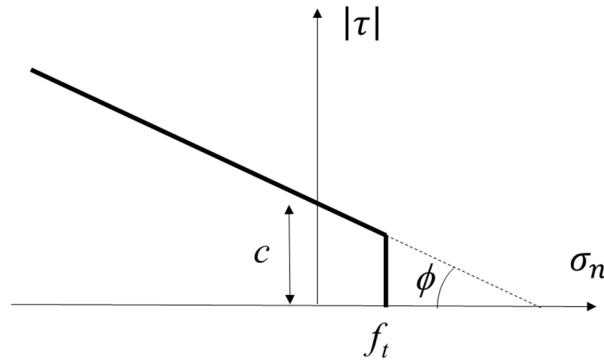
131 A tensile cut-off corresponding to tensile failure is added in order to complete the interface
132 failure criterion. It is defined by:

133

$$134 f(\sigma_n, f_t) = \sigma_n - f_t \quad (2)$$

135

136 where f_t is the tensile strength (Figure 2). In a tensile test of a quasi-brittle material, carried
 137 out under controlled displacement, the tensile strength corresponds to the peak of the stress-
 138 displacement curve.
 139



140
 141 Figure 2: Failure surface (shear stress versus normal stress) of brick/mortar interface.
 142

143 It can be noted that this criterion concerns the interface failure, but it can also include the
 144 failure of the mortar. So it can model globally the failure of the joint (brick/mortar interface
 145 and mortar).
 146

147

148 3. Materials

149

150 Depending on the brick and mortar compositions, various kinds of bonds can take place
 151 between mortar and brick. An interface is defined by the couple of brick and mortar. In this
 152 work, the two couples considered are typically dedicated to high temperature industries. The
 153 first one was made of dense silica bricks with a silica based mortar (used in coke ovens),
 154 denoted A. The second was made of high alumina bricks with a high alumina mortar, denoted
 155 B, which is used in blast furnaces. Information on the composition of the bricks and mortars
 156 is summarized in Table 1.
 157

w. %	A		B	
	Brick	Mortar	Brick	Mortar
SiO ₂	95	95	25	
CaO	< 3	< 1		
Al ₂ O ₃	< 1.5	< 1	72	90
Fe ₂ O ₃	< 1	< 0.5	< 1	< 1

158

159

160

Table 1: Composition of refractory bricks and mortars

161 Such refractory materials have to be stabilized before being tested. For interface A, the silica
 162 bricks were previously heated to stabilize quartz into cristobalite. For interface B, the high
 163 alumina bricks were previously stabilized into mullite mineralogical form. Then, green mortar
 164 was shaped between the two half samples, followed by hardening at room temperature during
 165 24 hours and drying at 110°C during 24 hours.

166 The interface strength obviously depends on the couple of materials, but workmanship is also
 167 a crucial factor. However, the purpose of this paper is to present the experimental methods
 168 developed to characterize the interface strength at high temperature, and to show how to use
 169 them to determine the parameters of the interface failure criterion.
 170

4. Compression - shear strength characterization

2.1 Experimental set-up

To characterize the shear strength from room temperature up to 1600°C, the loading set-up must be put in an appropriate furnace. This constraint induces two major difficulties: firstly, the set-up must be compact enough; secondly, the loading device must withstand high temperature. A possible solution to overcome these difficulties is to perform a slant shear test on two bricks pasted by one inclined mortar joint, as presented in Figure 3. This particular design of the specimen makes it possible to apply normal and shear stresses at the interface with a standard compression device. This type of test is a standard to characterize the adhesion of a repair material on concrete [29] and is also used to characterize the adhesion between two different concretes for example [30]. The limits of this test at room temperature and the influence of different shapes and material parameters were studied by Austin et al. [31]. The standard and usual test includes only one interface and is performed at room temperature while the specimen studied here includes two parallel interfaces and is performed at high temperature. The same test was used by Raffard et al. [32] coupled to optical measurement at room temperature to characterize the equivalent interface stiffness as a function of the mortar slant angle.

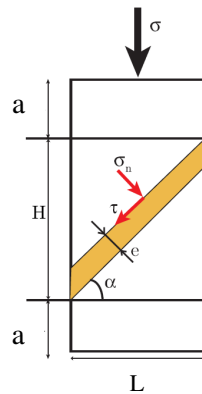


Figure 3: Slant shear test specimen.

The local normal compression σ_n and shear τ stresses applied on the brick/mortar interface are driven by the slant of the joint:

$$\begin{cases} \sigma_n = \sigma \cdot \cos^2 \alpha \\ \tau = \sigma \cdot \cos \alpha \sin \alpha \end{cases} \quad (1)$$

where σ is the global homogeneous applied compression stress and α is the angle between the mortar joint and the plane normal to the compression loading axis (Figure 3). The global homogeneous applied compression stress σ is computed by dividing the applied force F by the specimen transverse area S .

The identification of the cohesion and internal friction angle requires at least three different slant angles as three points are the minimum to obtain an objective line. The choice of the angle values is driven by mechanical constraints and experimental feasibilities. Indeed, to produce a shear fracture instead of a compression one, the angle must maximize the ratio of shear stress to normal compression stress. So, angles superior or equal to 45° are necessary (see Figure 4).

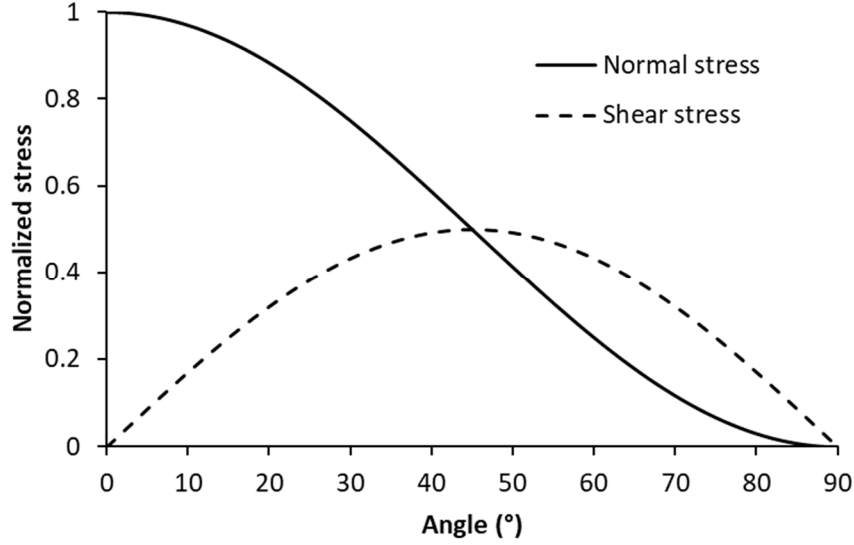


Figure 4: Evolution of shear and normal stresses at the brick/mortar interface as a function of the angle in a slant shear test.

Furthermore, the size of the specimen must be compatible with the size of the homogeneous temperature area in the furnace. This constraint is deduced from geometrical considerations and can be expressed by:

$$\begin{cases} \frac{e + L \sin \alpha}{\cos \alpha} + 2a \leq H_f \\ L \leq \phi_f \end{cases} \quad (2)$$

where a is the distance between the top (or the bottom) of the specimen and the closest intersection of the mortar joint with the lateral surface of the sample (see Figure 3). L is the largest specific dimension of sample section, while e is the thickness of the mortar joint. H_f and ϕ_f are respectively the height and diameter of the cylindrical area in the furnace chamber which provides a homogeneous temperature field. Finally, the chosen specimen shape is a parallelepiped of section $35 \times 35 \text{ mm}^2$ (i.e. $L = 35 \text{ mm}$) with $a = 15 \text{ mm}$. Its total height depends on the mortar joint angle α .

2.2 Specimen preparation and test conditions

The mortar thickness was 4 mm for samples A and 2 mm for samples B.

Samples A were first heated up to 1000°C , followed by a dwell of one hour to stabilize the mortar. Then, the samples were heated up or cooled down to the temperature of the test. A second dwell of 30 minutes at the temperature of the test was applied before performing the test to achieve the thermal treatment of the bonding. The tests were performed at 800°C , 1080°C and 1350°C for the three angles 45° , 55° and 65° of the mortar joint.

Samples B were first heated up to 450°C at a rate of 350°C/h , then up to 650°C at a rate of 125°C/h and finally to the temperature of the test at 325°C/h . A dwell of one hour was applied at the temperature of the test before performing the experiment. Tests (three for each material/temperature/angle combination) were performed at room temperature, 900°C and 1450°C for the three angles 45° , 55° and 65° of the mortar joint.

The tests were performed on a universal testing machine with a standard compression device with displacement control. The displacement speed rate was tuned to 0.5 mm/min .

243 As the interface strength is assessed by extracting the peak value of the load/displacement
 244 curve and the corresponding normal and shear stresses (estimated using equations (3)), the
 245 uncertainty of the calculation of the normal stress can be deduced from equation (3) and from
 246 uncertainties of stress σ assessment and angle α measurement. As σ is computed from the
 247 applied force F and the area ($L \cdot l$), the uncertainty U_σ of σ is [33]:
 248

$$249 \quad U_\sigma = \sqrt{\left(\frac{1}{L \cdot l}\right)^2 U_F^2 + \left(\frac{F}{L^2 \cdot l}\right)^2 U_L^2 + \left(\frac{F}{L \cdot l^2}\right)^2 U_l^2} \quad (3)$$

250 where L and l are the length and the width of the transverse section respectively. U_X is the
 251 uncertainty of X (F , L or l in that case). The relative uncertainty of X is:
 252

$$253 \quad {}^R U_X = U_X / X \quad (4)$$

254 The relative uncertainty of σ is then:
 255

$$256 \quad {}^R U_\sigma = U_\sigma / \sigma = \sqrt{({}^R U_F)^2 + ({}^R U_L)^2 + ({}^R U_l)^2} \quad (5)$$

257 The relative uncertainty of normal stress is:
 258

$$259 \quad {}^R U_{\sigma_n} = \sqrt{({}^R U_\sigma)^2 + (2 \tan \alpha)^2 U_\alpha^2} \quad (6)$$

260 The uncertainty of the determination of the shear stress can be deduced similarly from
 261 equations (3) and from measurement uncertainties of σ and α [33]. The relative uncertainty
 262 of shear stress is:
 263

$$264 \quad {}^R U_\tau = \sqrt{({}^R U_\sigma)^2 + \left(\tan \alpha - \frac{1}{\tan \alpha}\right)^2 U_\alpha^2} \quad (7)$$

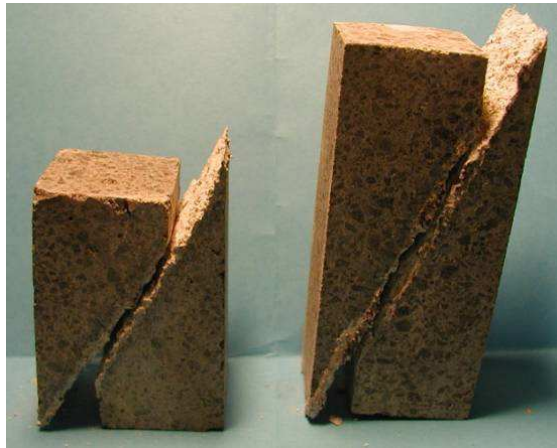
265 Assuming ${}^R U_F = 0.5 \%$ and ${}^R U_L = {}^R U_l = 1.5 \%$, then ${}^R U_\sigma = 2.2 \%$. Moreover, assuming that the
 266 total angle uncertainty is equal to $\pm 1^\circ$ ($U_\alpha = 1^\circ$), the relative uncertainty of the normal
 267 compression stress ${}^R U_{\sigma_n}$ increases from 3% to 4.8% for slant angles from 45° to 65° . For the
 268 shear stress, the relative uncertainty ${}^R U_\tau$ increases from 2.2% to 2.8%. Finally, due to the low
 269 value of stress, this uncertainty is negligible compared to possible material scattering and
 270 workmanship effects.
 271

272 2.3 Results

273 Figure 5 presents typical fractures after testing at high temperature. In samples A, cracks were
 274 clearly located at the interface between the mortar layer and the brick. In samples B, cracks
 275 appeared mostly in the mortar. In that case, we will consider the global joint failure (interface
 276 and mortar). In accordance with the concept of bond failure envelope [31, 34] it is proposed
 277 to use an analytical exploitation of the experimental peak load.
 278



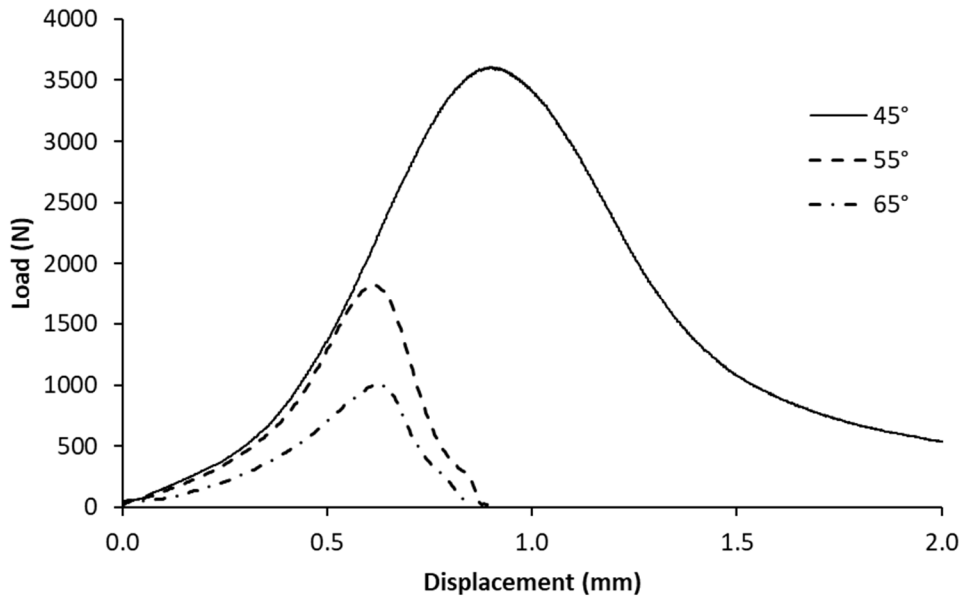
a) Specimens A at 1080°C



b) Specimens B at 900°C

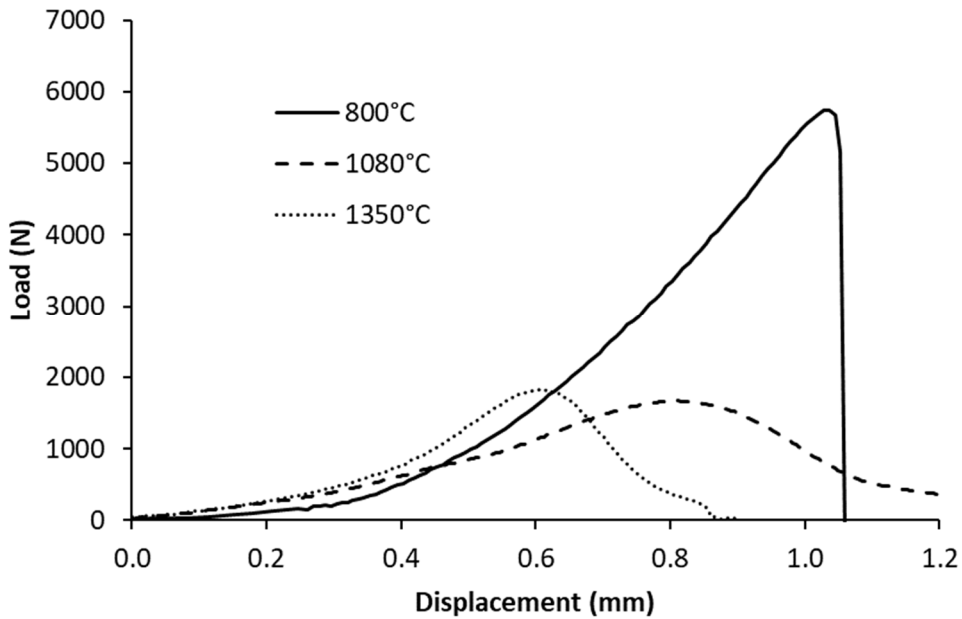
Figure 5: Specimens after testing (slant shear tests)

Figure 6 presents typical load versus displacement curves obtained during the test for specimen A. The different curves correspond to the three different joint slants tested at the same temperature of 1350°C. The maximum load (corresponding to fracture) decreases with the slant angle increase. Figure 7 presents the effect of temperature for a constant joint angle of 55°. It appears that, after a strong decrease between 800°C and 1080°C, the maximum load is stabilized for higher temperatures. Furthermore, the curves exhibit a slight evolution of the whole behaviour of the sample from brittleness to nearly ductile. Since the silica bricks are stabilized, this is due to the mortar behaviour evolution. However, the fracture is still located at the interface and it is essentially brittle.



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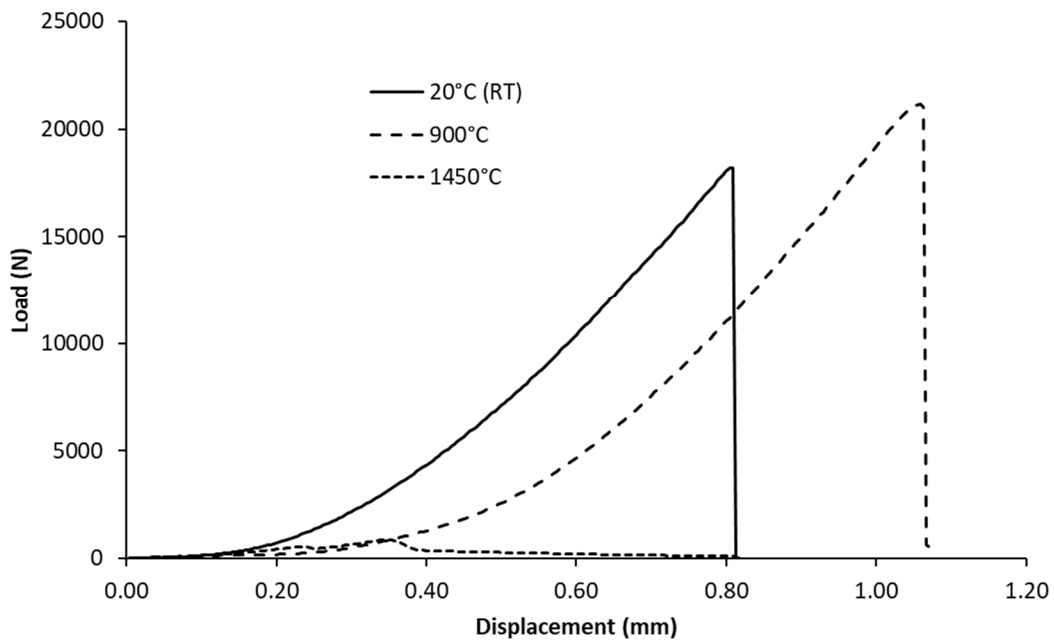
Figure 6: Load versus displacement curves for specimen A at 1350°C for three joint angles (slant shear tests)



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Figure 7: Load versus displacement curves for specimen A with a joint slope of 55° at different temperatures (slant shear tests)

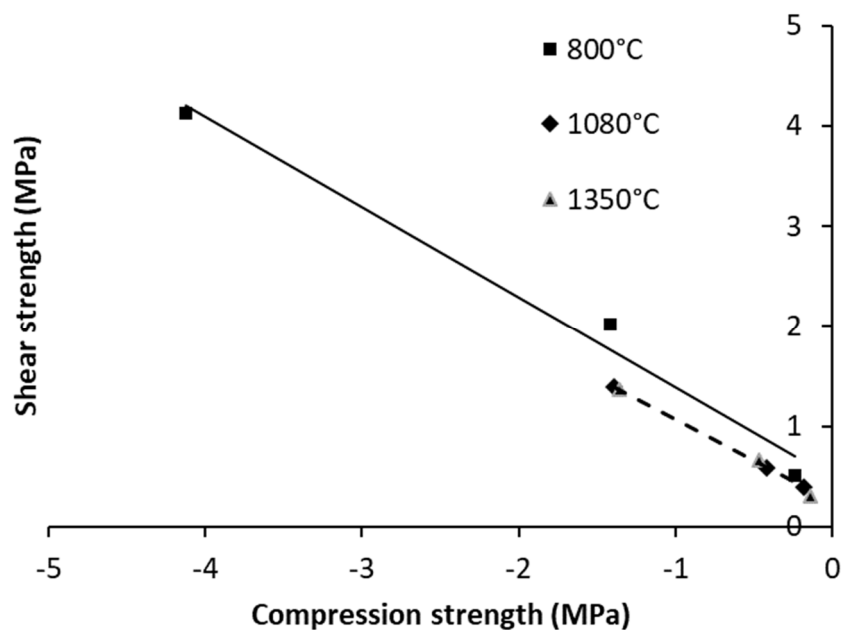
For specimen B, typical results are presented in Figure 8. It shows (for an angle of 65°) that the maximum load of specimen B, after a slight increase until 900°C, drops drastically to almost zero. The brick/mortar interface no longer has any strength at high temperature.



316

317 Figure 8: Load versus displacement curves for specimen B with a joint slope of 65° at
 318 different temperatures (slant shear tests)
 319

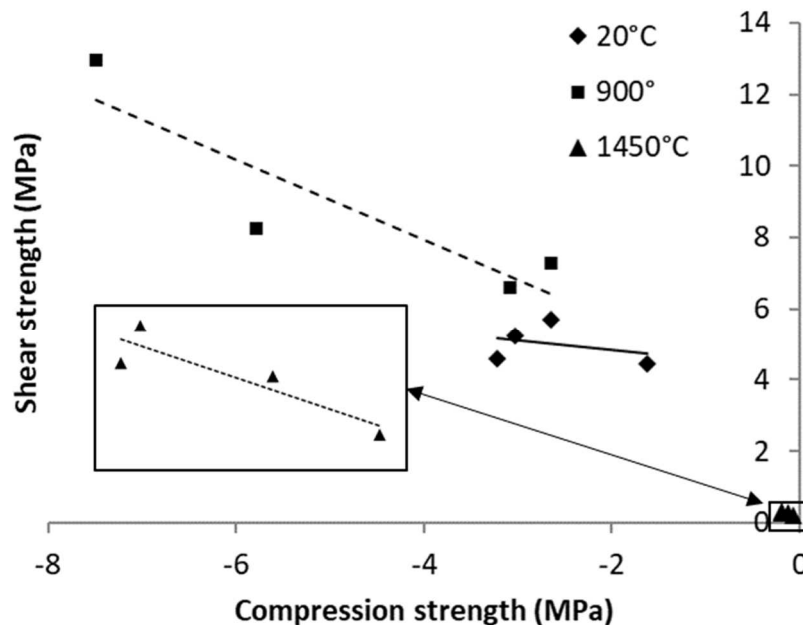
320 Figure 10 shows the Mohr-Coulomb graph extracted from the load versus displacement curves
 321 of specimen A at the different temperatures tested. The ultimate strength points define a line
 322 from which the cohesion and friction angle for each temperature can be determined. The
 323 difference between 1080°C and 1350°C is small, whereas a visible difference appears for the
 324 cohesion between 800°C and 1080°C. Moreover, the friction angle does not appear to be
 325 strongly temperature dependent.
 326



327
 328
 329

Figure 10: Mohr-Coulomb lines for specimen A at 800°C, 1080°C and 1350°C

330 Figure 11 presents the Mohr-Coulomb graph extracted from the load versus displacement
 331 curves on specimen B at the different temperatures tested. Firstly, there is no obvious tendency
 332 linked to the temperature. Indeed, whereas the shear strength seems to be almost independent
 333 of normal compression stress at 20°C, there is a more classical Mohr-Coulomb dependence
 334 with an enhancement of the strength value at 900°C, but a drastic drop in strength at 1450°C.
 335 This evolution is linked to the evolution of the mortar between 900°C and 1450°C. Whatever
 336 the results, this test makes it possible to quantify the shear strength evolution of the
 337 brick/mortar interface with the temperature and to identify a maximum reached at around
 338 900°C.
 339



340
 341 Figure 11: Mohr-Coulomb lines for specimen B at 20°C, 900°C and 1450°C
 342
 343

344 3. Tensile strength characterization

345
 346 In the previous section, the Mohr-Coulomb yield surface was considered to model the mixed
 347 compression-shear strength. This section deals with the identification of the tensile cut-off
 348 corresponding to tensile failure in order to complete the interface failure criterion.
 349

350 3.1 Experimental set-up

351
 352 In this work, high temperature tensile strength tests were performed using a universal testing
 353 machine equipped with a high temperature furnace (Figure 13). The force was measured with
 354 a classic load cell. A cooling device is set between the furnace and the load cell to protect the
 355 load cell. The displacement of the crosshead was also measured. However, the displacement
 356 measurement does not require accuracy since only the force peak is required to determine the
 357 tensile strength.
 358 The experimental set-up has to be compact (to be put in the furnace) and to withstand high
 359 temperatures. To ensure a pure tensile failure, it is also necessary to provide good specimen
 360 alignment. Consequently, the clamping device must withstand high temperature and its design
 361 has to ensure its installation in the confined furnace workspace (Figure 13). To that purpose,

362 a new set-up was designed. It consists of three parts: two clamps and an assembly including
363 the specimen and two linking wires.
364



365
366
367

Figure 13: Universal testing machine with the furnace (AET ref. OF 25 957 Type SP)

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The assembly is made up of a couple of cylindrical refractory units joined with mortar (Figure 14). Two wires, inserted in the units and going through them thanks to shouldered holes, allow the blocks to be clamped. A ball at the end of each wire stops translation. Each wire is made of nickel-chromium alloy (e.g. Nikrothal 70) to resist high temperature. It has a diameter of 2 mm so that it supports the applied stress while being flexible enough to ensure the alignment of the loading “chain”. Finally, it must be long enough for the specimen to be positioned in the middle of the furnace. Both wires are gripped with specific clamps located outside the furnace, linked to cooling devices and to the testing machine. As expected, using these specific clamps and wires the specimen can be aligned in the force direction.

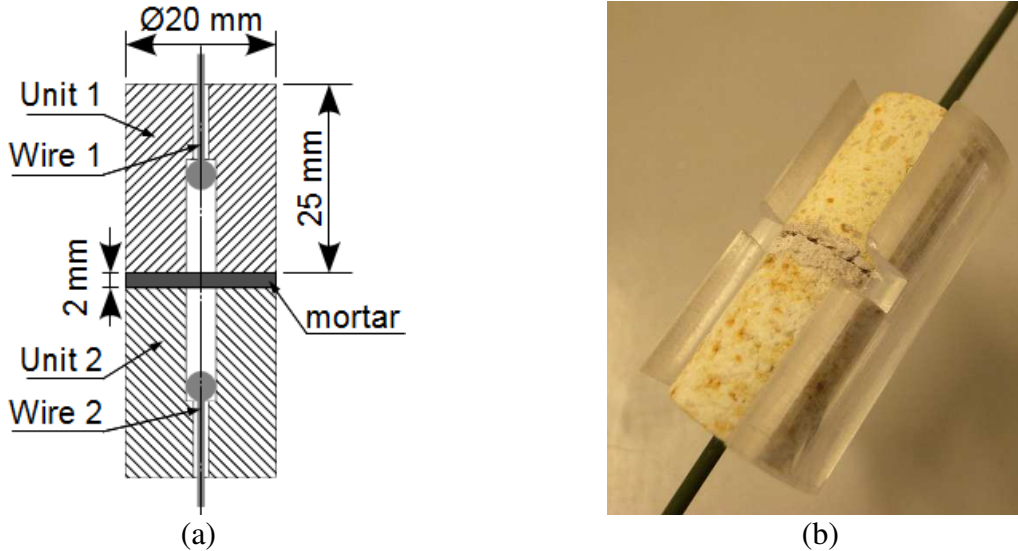
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380

3.2 Specimen preparation and test conditions

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390

It is well known that specimen dimensions and aggregate size have an influence on brittle fracture [35, 36]. Assuming that the probability of cracking increases with the joint area, it can be deduced that the smaller the sample, the higher the tensile strength for the interface. Knowing that in usual refractory linings the area of contact between bricks and mortar (2 to 4 mm thick) is around $200 \times 80 \text{ mm}^2$, the specimens should have the same area of contact. But the specimen size is restricted by the furnace workspace as mentioned previously. The specimens were therefore chosen as large as possible, compatible with the furnace dimensions. Finally, the cylindrical units had a diameter of 20 mm, a height of 25 mm and the joint was 2 mm thick for samples B (Figure 14a). Therefore, the strength values obtained herein must be considered as an upper bound.

391



392
393
394 Figure 14: Specially designed specimen for high temperature tensile test: principle (a),
395 specimen and mould (b)
396

397 Ensuring a good alignment of the loading “chain” requires meticulous preparation of
398 specimens. To that purpose, the units were obtained by core drilling. Then the core samples
399 were ground to allow the drilling of coaxial holes. The two units were assembled using a
400 specific mould (Figure 14b) to ensure the good alignment between the two cylinders and to
401 control the mortar thickness. After air drying for 24 hours, the specimen was removed from
402 the mould to be pre-heated at a temperature of 300°C.

403 The tensile test can be divided into 3 main stages. In the first step the specimen was put into
404 the furnace, then tightened and clamped through the wires, heated up to the set point value at
405 a rate of 700 °C/h and stabilised during half an hour. In the second stage, the measured force
406 was reset to zero because the wires and load cell had expanded. The test started applying a
407 displacement to the upper crosshead. The last stage consisted in stopping the heating device,
408 cooling down the specimen and removing it.

409 Tensile tests were performed on samples A at room temperature and on samples B at three
410 temperatures: room temperature, 900 and 1200°C. For room temperature, the tests were
411 performed with a displacement rate of 0.5 mm/min. For high temperature tests, the
412 displacement rate was tuned to 30 mm/min to avoid wire creep. This displacement rate has a
413 great influence at high temperature on the Nikrothal cable behaviour and a smaller influence
414 on the refractory behaviour up to 1200°C (the influence is higher for higher temperatures).
415 But the interface strength was assumed to be independent of the strain rate.

416 The tensile strength f_t was determined using the equations:
417

$$418 \quad f_t = \frac{F_{\max}}{S} \quad (10)$$

$$419 \quad S = \pi \frac{D^2 - d^2}{4} \quad (11)$$

420
421 where F_{\max} is the maximum load reached before the fracture of the sample, S is the area of the
422 transverse section, D and d are the outer and the inner diameters of the cylindrical unit
423 respectively.

424 The uncertainty of the determination of the tensile strength f_t can be deduced from equations
 425 (10, 11) and from the measurement uncertainties of F_{max} , D and d [33]. The relative
 426 uncertainty of tensile strength is:

427

$$428 \quad {}^R U_{f_t} = \sqrt{\underbrace{{}^R U_F^2}_{U_1^2} + \underbrace{\left(\frac{2D^2}{D^2 - d^2}\right)^2 {}^R U_D^2}_{U_2^2} + \underbrace{\left(\frac{2d^2}{D^2 - d^2}\right)^2 {}^R U_d^2}_{U_3^2}} \quad (12)$$

429

430 where ${}^R U_F$, ${}^R U_D$, and ${}^R U_d$ are the relative uncertainties of F , D and d respectively. For the sake
 431 of simplicity, let us give a name to each of the three parts of the relative uncertainty (equation
 432 12):

433

$$U_1 = {}^R U_F \quad (13)$$

434

$$U_2 = \left(\frac{2D^2}{D^2 - d^2}\right) {}^R U_D \quad (14)$$

435

$$U_3 = \left(\frac{2d^2}{D^2 - d^2}\right) {}^R U_d \quad (15)$$

436

437 Figure 15 represents the sensitivity of the tensile strength to the outer diameter D for an inner
 438 diameter $d = 4$ mm. Each part of the tensile strength uncertainty (U_1 , U_2 , U_3) and the combined
 439 relative uncertainty ${}^R U_{f_t}$ (denoted U_f in Figure 15) are plotted versus the outer diameter, with
 440 ${}^R U_F = 0.5$ %, ${}^R U_D = 2.5$ % and ${}^R U_d = 5$ %. The combined uncertainty is a quadratic fraction of
 441 D while all other parameters are constant. As a result, uncertainty decreases with an increasing
 442 diameter. For a larger diameter, the uncertainty decreases more gradually and tends to an
 443 asymptotic value equal to the square root of the quadratic sum of the relative uncertainties.
 444 The second term U_2 is larger than the others and the combined uncertainty is approximately
 445 twice as large as the relative uncertainty of the measurement of the outer diameter. As a result,
 446 the chosen diameter (20 mm) appears to be a good compromise to ensure homogeneity,
 447 compatibility with the furnace workspace and satisfactory uncertainty.

448

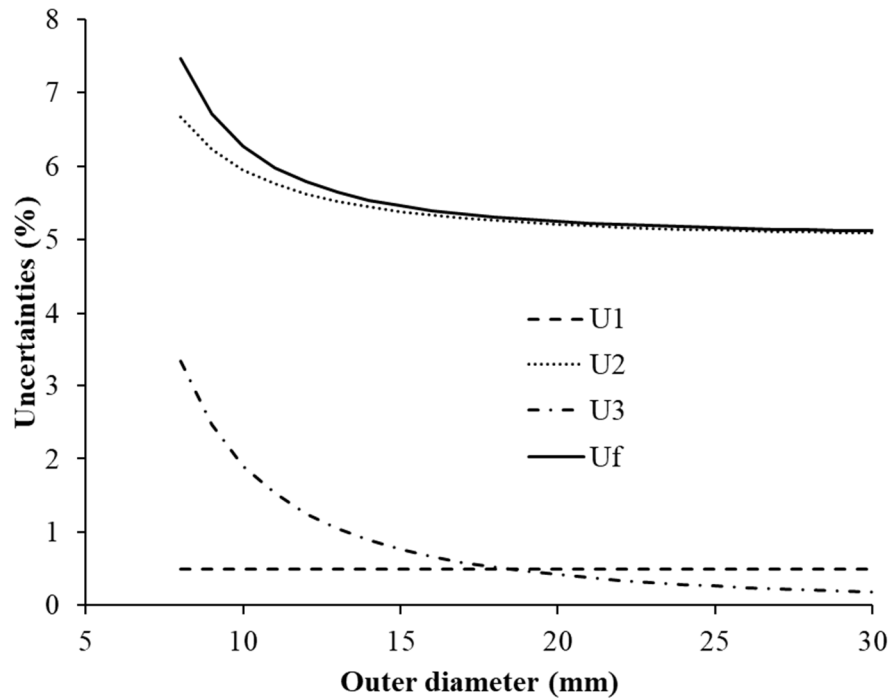


Figure 15: Uncertainties of tensile strength versus outer diameter

3.3 Results

Figure 16 presents typical load versus displacement curves obtained during the tensile test. The curves correspond to tests carried out for two specimens B at 900°C. The first nonlinear part of the curve before cracking can be explained by the nonlinear behaviour of the interface but also by the straightening out of the wires followed by their creep. Accordingly, it is difficult to deduce a behaviour model of the specimen. However, the tensile strength can be determined from the maximum load. The curve for specimen B-2 shows a load release around 4 mm of displacement. This might be due to the sliding of the wires into the bricks or to a local crushing in the area of contact between a wire ball and the specimen. Once the balls made at the end of the wires have found their places in the holes, the load increases again as if nothing had happened. It can be assumed then that this technical problem does not influence the tensile strength. After the maximum load value is reached, the load decreases very quickly for both curves because of the total failure of the joint.

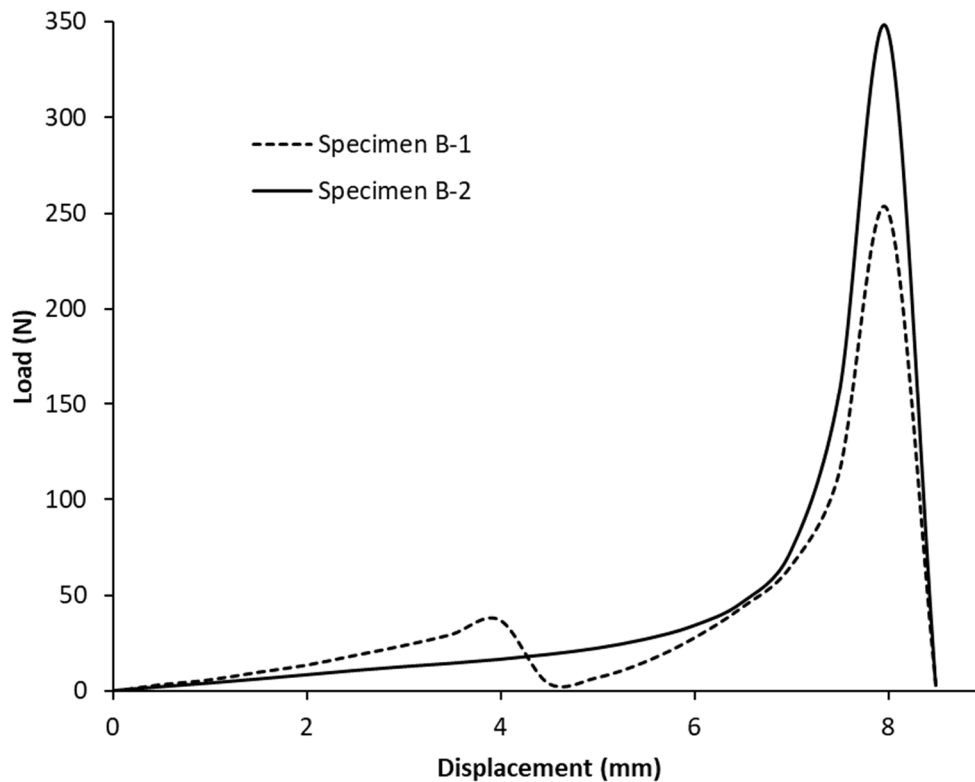


Figure 16: Load versus displacement for sample B at 900°C

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472 The tensile strengths f_t for specimens B-1 and B-2 are 0.82 MPa (load = 247 N) and 1.1
 473 MPa (load = 342 N) respectively.

474

475 Figure 17 presents the evolution of the tensile strength versus temperature for specimens B.
 476 The curve can be divided into two parts. The tensile strength remains nearly constant from
 477 room temperature up to 900°C. In contrast, the second portion of the curves reveals a sharp
 478 decrease. The tensile strength of specimens B is low at high temperature, which implies joint
 479 opening (brick/mortar separation) when they are submitted to a low tensile load in a structure.

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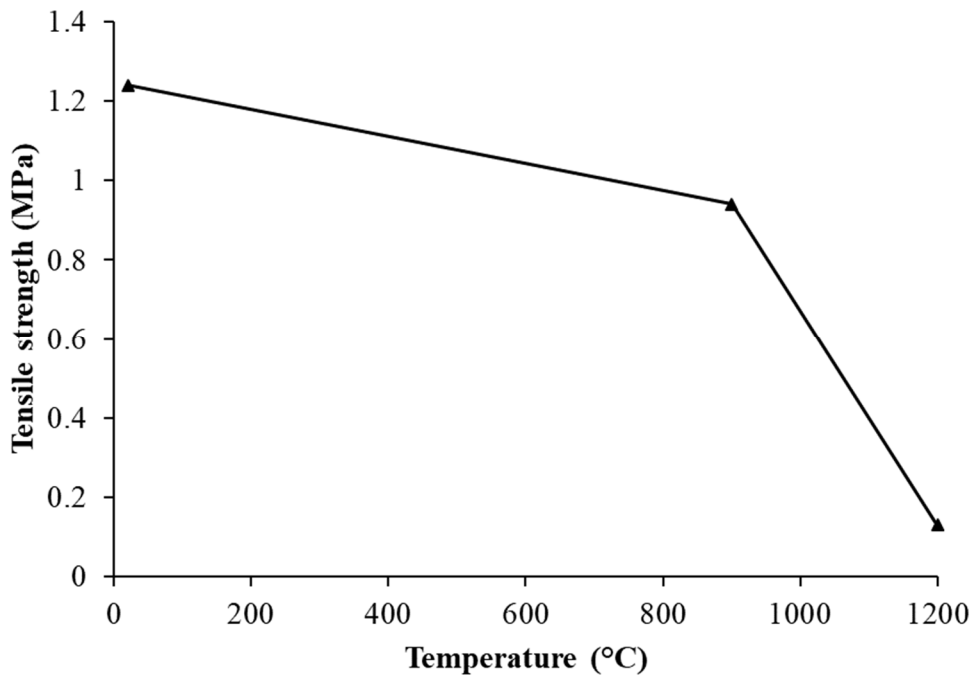


Figure 17: Tensile strength versus temperature for specimens B.

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Concerning specimen A, the tensile strength at room temperature is very low (0.2 MPa). It corresponds to the failure of the brick/mortar interface (see Figure 18 with the penny shape of the mortar after failure). This shows that the bond between mortar and brick is weak. It is the reason why no tests were performed at high temperature for specimens A. The tensile strength can be considered as zero whatever the temperature for specimens A.



Figure 18: Specimen A failure in tension.

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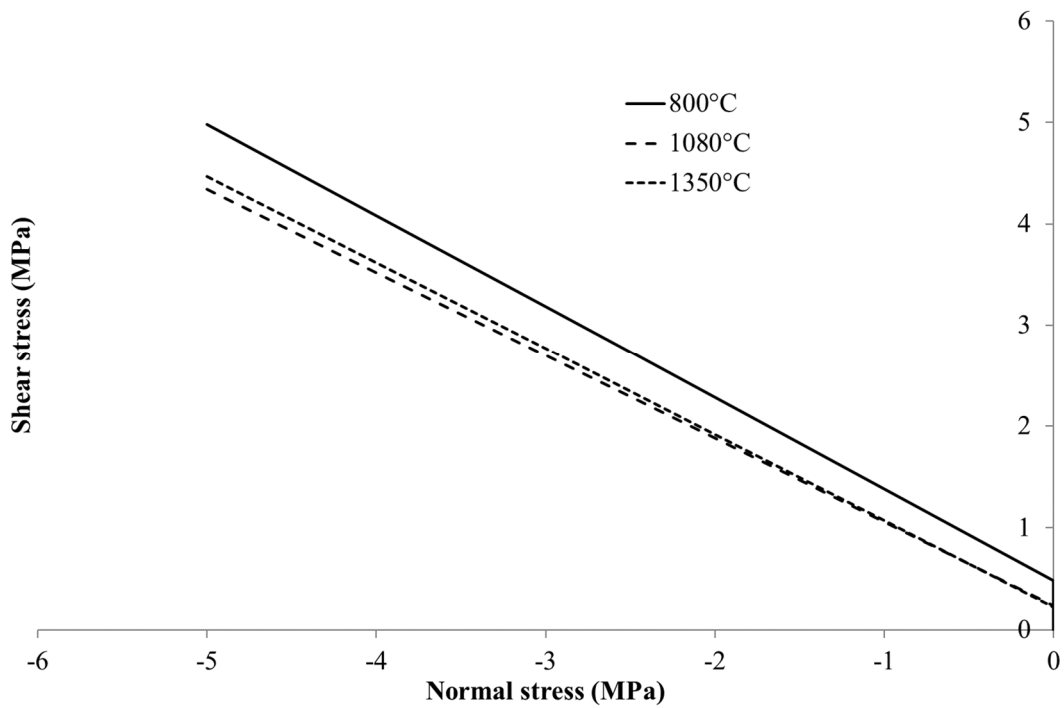
4. Failure criterion identification and discussion

Based on the tensile tests and slant shear tests performed in the previous sections, the different parameters of the Mohr-Coulomb failure criterion coupled with a tensile cut off were determined. Their values are given in Table 2. The corresponding failure surfaces are presented in Figures 19 (specimens A) and 20 (specimens B) for different temperatures.

Temperature	Specimen A			Specimen B		
	c (MPa)	tan ϕ	f_t (MPa)	c (MPa)	tan ϕ	f_t (MPa)
R.T.			0.2	4.26	0.28	1.29
800°C	0.48	0.90				
900°C				3.44	1.12	0.99
1080°C	0.24	0.82				
1350°C	0.22	0.85				
1450°C				0.15	0.81	0.14

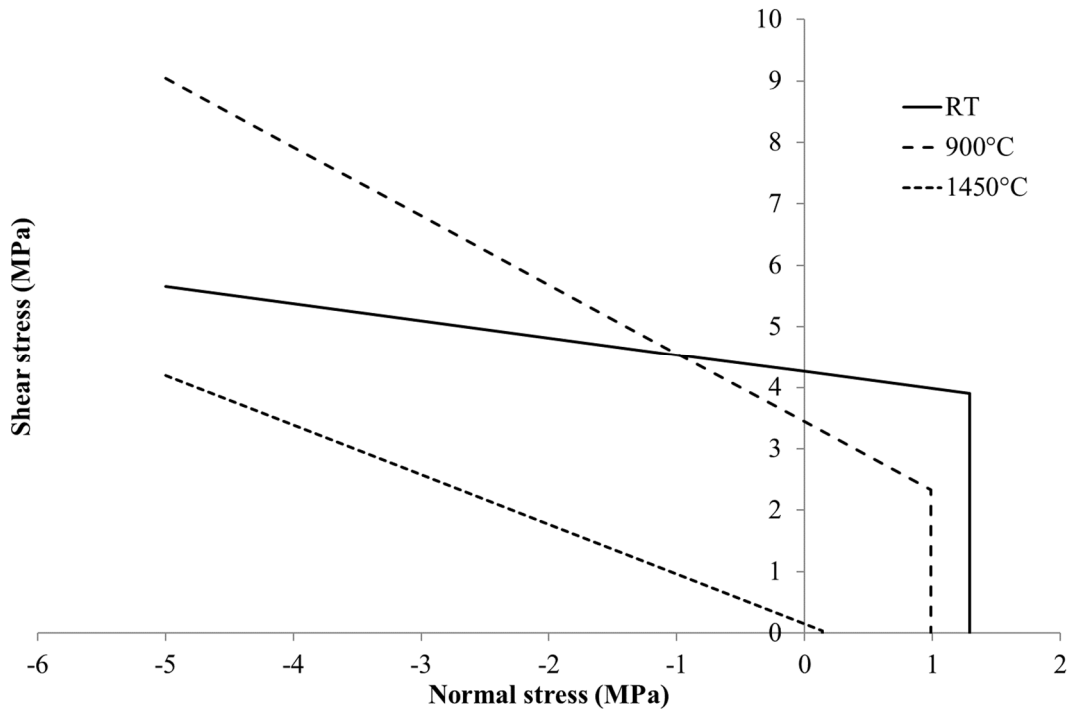
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Table 2: Cohesions, friction angles and tensile strengths identified at different temperatures



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Figure 19: Failure surfaces of specimen A at different temperatures.



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517 Figure 20: Failure surfaces of specimen B at different temperatures.
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519 For specimens A, the friction angle is almost independent from temperature, while the
520 cohesion is temperature dependent (but the values are small, near zero). The tensile strength
521 is also small and can be considered as zero. The brick/mortar interface is very weak. No real
522 bond is created between the two materials during heating, and a small shear or tensile load
523 causes interface failure. Brick and mortar can be considered as two independent parts in
524 contact with friction.

525 For specimens B, friction angle, cohesion and tensile strength are temperature dependent. A
526 marked decrease in the specimen properties can be observed for temperatures higher than
527 900°C. In particular at 1450°C, the interface strength is weak, as for specimens A. These
528 observations on mechanical behavior are coherent with the possible development of an
529 increasing amount of glassy phase inside the mortar when the temperature increases. As
530 previously pointed out, in the case of specimens B, the failure appeared mostly in the mortar:
531 the mortar is weaker than the brick/mortar interface. So the joint property decrease at high
532 temperatures is due to the decrease of mortar strength at these high temperatures.
533

534 535 **5. Conclusion**

536
537 Experimental characterization of the strength of the brick/mortar interface is a key point to
538 ensure the reliability of masonry computation, as the brick/mortar interface is often the
539 weakest link of the assembly. Although the characterization of interfaces at room temperature
540 has been extensively studied in civil engineering, there is a real lack of data for high
541 temperature masonry based on refractory materials.

542 Two set-ups and sample shapes were developed to carry out tensile and slant shear tests at
543 high temperature. For the first one, dedicated clamping devices were designed and tests were
544 performed in a temperature range from room temperature up to 1200°C. Results have allowed
545 us to identify the tensile strength of the brick/mortar interface depending on the temperature.
546 The slant shear test was carried out in the temperature range from room temperature up to

547 1450°C. Mohr-Coulomb parameters of the brick/mortar interface (i.e. cohesion and friction
548 angle) were identified and found to be temperature dependent.
549 For both methods, the uncertainties of the strength estimation induced by the specimen
550 geometry and measurement device were computed. Results have shown that the uncertainty
551 is lower than 5% for tensile, compression and shear strengths. These values confirm that the
552 discrepancy between experimental values can be explained mainly by the discrepancy
553 between the samples (i.e. mortar batch, refractory heterogeneity).
554 The two different brick/mortar couples tested are representative of the two possible joint
555 failures: brick/mortar interface or mortar. As a result, the failure surfaces obtained (Mohr-
556 Coulomb criterion) represent the global failure of the joint and not only the failure of the
557 brick/mortar interface.
558 In conclusion, the two experimental set-ups proposed here enable a complete and accurate
559 characterization of the brick/mortar interface strength at high temperature to be carried out.
560 The relative simplicity of these devices may facilitate their use in the refractory community
561 to enlarge the knowledge on the ultimate strength evolution with temperature of such
562 interfaces.

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571 **References**

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