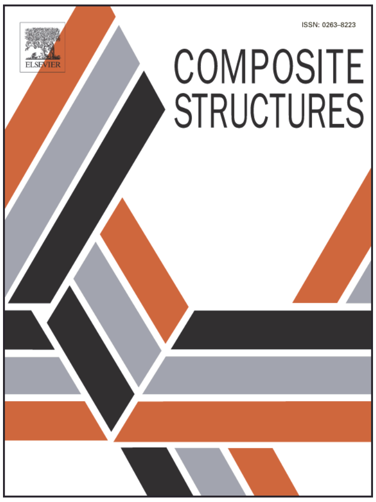
Investigation of creep phenomenon on composite material for bolt connections

Accepted Manuscript



Investigation of creep phenomenon on composite material for bolt connections

A. Scattina, D. Roncato, G. Belingardi, G. Martino

PII: S0263-8223(15)00753-9
DOI: http://dx.doi.org/10.1016/j.compstruct.2015.08.061
Reference: COST 6765

To appear in: *Composite Structures*

Please cite this article as: Scattina, A., Roncato, D., Belingardi, G., Martino, G., Investigation of creep phenomenon on composite material for bolt connections, *Composite Structures* (2015), doi: http://dx.doi.org/10.1016/j.compstruct.2015.08.061

Investigation of creep phenomenon on composite material for bolt connections

A. Scattina[1*], D. Roncato[2], G. Belingardi[1], G. Martino[2]

[1]*Dipartimento di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Torino, Italy*

[2]*Centro Ricerche Fiat, strada Torino 50, 10043 Orbassano, Italy*

Corresponding author: Alessandro Scattina, Dipartimento di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy, Tel.: +390110906913; Fax: +390110906999; email: alessandro.scattina@polito.it

Investigation of creep phenomenon on composite material for bolt connections

One of the main target in the automotive design is the weight reduction. This reduction leads to the reduction of the gas emissions. The designers tend to use innovative materials for the automotive field such as plastics and composites. To use the right material for the right application, multi material solutions are increasingly adopted. To join dissimilar materials, solutions like adhesive, bolt and nuts, riveting are necessary. It is necessary to know the behaviour of the materials to be joined, under different loading conditions to ensure the joint. In this work, a bolt connection between composite and aluminium plates has been considered. The behaviour of a carbon fibre reinforced material under compression load, taking into account creep is studied. A specific experimental equipment has been design and built. A series of experimental compressive tests, in the laminate thickness direction, have been done on carbon fibre reinforced material specimens. Different set-up in terms of temperature, compression load and surface roughness have been investigated. The obtained results are presented and discussed. A mathematical model will be proposed for interpolation of the obtained results. Finally, a possible strategy for reducing the tight loss in the initial phase of the joint life is proposed.

Keywords: creep; carbon fibre reinforced plastic; bolt connection

1. Introduction

Nowadays one of the main targets in the automotive design is the weight reduction. This is a very important aspect because it is one of the key factor for the reduction of both fuel consumption and pollutant emissions. Indeed, the gas emissions, in particular the production of the carbon dioxide, are directly proportional to the fuel consumptions that are directly influenced by the weight of the car. Consequently, the reduction of the weight leads to the reduction of GHG emissions that are responsible of the present impressive climate change. On the other side, along the years, the weight of the car has had a continuous growth. This is due to the tendency to equip vehicles with more devices and gadgets. In this overview, it is clear as in the design of the new vehicles the attention is focused on the containment of the structures weight. To this aim, the designers put their attention on the use of lightweight materials such as reinforced plastics and composites. The target is to use the right material for the right application. For this reason, even more often, multi material solutions are adopted in the design. In these cases, it is also necessary to use different joining technologies. Indeed, the traditional joining technologies adopted in the car manufacturing, such as the spot welding, cannot be used when different types of material have to be joined together. Consequently, solutions like adhesive, bolt and nuts or riveting are taken into consideration. To ensure a correct working of the connection, it is also necessary to investigate into details and to know the behaviour of the materials to be joined under different loading conditions.

In this frame, the research activity, whose results are reported in this work, has been focused on the study of a bolt connection between a part made in aluminium and a part made in composite material. It is well known as, in this type of connection, the bolt is tight to give enough compression force between the joined members. However, creep phenomenon, in particular on the composite part, could cause a loose of tight of the bolt with consequently malfunction of the joining with also possible problems from a safety point of view, depending on the considered application. For these reasons, in this work, the creep effect due to compression load on a carbon fibre material in epoxy resin has been investigated. In particular, the behaviour in a direction perpendicular to the fibre has been studied. A specific experimental testing machine has been developed to this aim. With this machine, a series of experimental creep compression tests have been carried out. The effect of the temperature, the amount of the load and the surface roughness have been investigated.

1.1 State of the art

Usually the matrix material of a composite has a viscoelastic behaviour. For this reason, the composite materials are subjected to creep phenomenon [1]. The creep effects on material are studied from many years, and different behaviour models have been proposed, as discussed for example by Findley et al. [2].

In particular, the creep behaviour of the composite is influenced by different aspects such as the temperature, the stress level, the moisture and so on [1]. Some different works, where the creep behaviour in the direction of the fibre is considered, have been published in the past. In this case the behaviour of the material is driven both by the fibres and by the matrix. Test on creep in composite in the fibre direction has been carried out by Kim and McMeeking [3]. Maksimov and Plume have investigated the long term creep behaviour of aramid fibres [4]. Bending and tensile creep testing on carbon fibre/epoxy matrix composite have been studied by Goertzen and Kessler [5]. Accelerated tests has been done by Raghavan and Meshii [1], by Abdel-Magid et al. [6] and by Scott et al. [7]. The effect of different types of fibre materials has been investigated by Maksimov and Plume [8]. Longitudinal compressive load and long term tests has been performed by Scott and Zureick [9] on beams made in pultruded e-glass/vinylester composite for civil-engineering construction. Always concerning the civil applications, similar studies have been carried out by Holmes and Rahman [10], by Mosallam and Bank [11, 12] and by Wang et al. [13]. Kouadri-Boudjelthia et al. [14] have studied the effect of the temperature, the load and the crystallinity rate of a composite material made of unsaturated polyester matrix and reinforced with randomly oriented type C glass fibres. The creep behaviour of the material has been modelled using power law formulation. Other prediction models for the creep behaviour have been proposed by Guedes et al. [15] and by Raghavan and Meshii [1].

The creep behaviour of composite materials in the direction perpendicular to the fibre is mainly governed by the matrix material as demonstrated by Guedes et al. [16]. This behaviour can contribute to the relaxation phenomenon in bolted connections. Also in this case some studies have been carried out in the past for example by Weerth and Ortloff [17], Pang and Wang [18] and by Chen and Kung [19]. Specific works on the bolt connection of parts made with composite materials have been published by Shivakumar and Crews [20]. They studied a connection of two plates made of T300/5208 graphite/epoxy, predicting the relaxation after a long period of time. The temperature and the moisture effects have been also considered in the study. Shivakumar and Crews [20] have also proposed a predictive model. A study of E-glass/vinylester bolted joints has been carried out by Fox [21]. In this study relaxation and shear tests were carried out. Bolted connections with composite, in particular E-glass/vinyl-ester have been studied by Weerth and Ortloff [17]. The loss in the tight load has been measured and the data have been fitted with a power law equation, which allows the prediction of the relaxation. Similar power law formulation has been used to predict the loss of load in the bolt by Pelletier et al. [22].

2. Materials & Methods

2.1 Material

In this work the compression creep behaviour of a carbon fibre/epoxy resin has been investigated. In particular, a twill carbon 2x2 800 UTS 24K with epoxy resin with a cure of 90 minutes at 120 °C have been chosen. The stacking sequence has been one layer of 380 gsm and seven layer of 800 gsm. The 380 gsm layer is on the side of the mould. The cured ply of 800 gsm is 0.88 mm thick while the one of 380 gsm is 0.45 mm thick. The total thickness of the laminate is 6.6 mm. It has been decided to use specimens with a cylindrical shape, with a diameter of 20 mm, as shown in Figure 1. The properties of the material are reported in Table 1.

2.2 Testing machine

To perform the creep compressions tests a dedicated testing machine has been developed. The testing machine is shown in Figures 2 and 3. It is based on a lever principle. It is characterized by a frame where the lever is hinged. The compression stress is created applying a load on one side of the lever, then the lever push on a column, which applies the compressive stress on the specimens. The machine has been designed to test at the same time three different specimens. These specimens have been positioned between rigid metal plates. These plates are positioned between two steel columns, one above and one below the test area, the upper column applies the load to the plates. To ensure only load perpendicular to the specimens, the plates are driven by two additional smaller lateral columns. The lever in the upper part is in contact with the main column only in a single point, by means of a steel ball positioned on the upper part of the column. The applied load is measured with a load cell positioned in the lower part of the column. To measure the compression displacement, extensometers are fixed between the steel plates where the specimens are positioned. The testing machine has been designed to be used with a climatic chamber in order to make experimental tests at different temperatures. The plates with the specimens can be positioned inside the climatic chamber while the frame of the machine is positioned outside the chamber as shown in the Figures 2 and 3.

3. Experimental tests

A series of creep compression tests have been carried out. The tests have been approached following the general rules suggested by the ASTM D2990, which provides the standard test methods for compressive creep of plastics. However, our tests have been more oriented on the considered specific application: the bolted joint. For this reason, for example, in order to study the behaviour of the material perpendicular to the fibres, the geometry of the specimen is different from that defined in the ASTM standard.

It is worth of notice that the applied test procedure is of the constant load type. The duration of each of the tests has been set in one week. In this way only the first phase of the creep phenomenon, that includes the most relevant changes in the deformation, can be evaluated. However, this choice is justified because we are interested to study what happens in the first period after the tight of the bolt. In this way, it is possible to verify if some actions can be done in the production process to improve the durability of the connection.

The influence of three different parameters on the results have been considered. In particular they are:

- Temperature: two levels, room temperature and 80 °C
- Pressure: three levels, 30, 40 and 50 MPa
- Roughness of the specimen surface: two levels, rough and smoothed

For what concerns the temperature levels, the joint considered as reference in this study can work both at room temperature and at higher temperature, this justify the chosen second level of temperature. It is worth of note that work temperature can also be lower that 0°C, but, as discussed in the introduction, it is well known that the highest sensitivity is for temperature greater than room temperature, therefore at the moment cold environment has not been considered. For what concerns the applied load, the joint is designed to have a pressure of 40 MPa in the zone of the washer. Thus, to investigate the influence of the applied load, it has been increased and decreased of 10 MPa with respect to the design value to define a pressure range. In this first step of analysis, the joint has been considered under a static point of view, without considering the fluctuation of the loads, which are applied during normal operation. Also the roughness of the surface has been examined. As it is possible to see in Figure 1, one side of the specimen, the one which is in contact with the vacuum bag, shows a roughness higher than that in the contact with the mold. Preliminary experimental tests show as the entity of the compression deformation during creep compression tests, can be comparable with the roughness of the surface. For this reason also this parameter has been taken into consideration. A measure of the roughness has been also made as described in the following sections. In the text, the surface named “rough”, refers to specimens in the as-produced conditions, while for the specimens named “smoothed”, the surface in contact with the vacuum bag has been subjected to a mechanical process of finishing with milling machine.

3.1 Experimental results

A set of the compression displacement curves as a function of the time is shown in Figure 4 for nine different specimens examined under the same testing conditions. For each considered testing configuration, at least three specimens have been tested. In the following, for each examined configuration the average curve (continuous line) and the average curve plus or minus the standard deviation (dotted lines) are presented. The diagrams show the compression displacements starting from the time when the applied load reaches its steady state level. The main part of the total compression relaxation is reached within the first twelve - twenty-four hours. Then the displacement has a more moderate increase that seems governed by a linear equation.

The influence of the temperature is presented in Figure 5, where the compression displacement curves at the two different temperatures, for the configuration with rough specimens and an applied pressure of 40 MPa, are presented.

The influence of the applied pressure is presented in Figure 6, where, for the specimens with rough surface, the compression displacement curves obtained at 25°C, are shown.

The influence of the type of the roughness is shown in Figure 7. A further investigation on this aspect has been made evaluating the roughness *Ra* on the surface of the specimen in contact with the vacuum bag. In Figure 8 the results of these measurements have been summarized. In particular, in the figure the average values obtained measuring the roughness on two perpendicular diameter are presented. The roughness has been measured on all the specimens at disposal in this activity. For each typologies of specimen, the measurements have been replicated three times and then the average values have been calculated.

4. Discussion

As expected and also discussed in the literature, an increase of the temperature increases the resulting relaxation of the material as shown in Figure 5. The same trend has been obtained also considering the other configurations in terms of pressure and surface roughness, i.e. an increment of the applied pressure or of the surface roughness increases the resulting relaxation.

Considering the influence of the pressure, Figure 6, the data are more scattered, but, as expected, the tendency is to have a higher compression displacement with higher pressure. The trend is not linear, it means that the curves with a pressure of 30 and 40

MPa are closer than those at 40 and 50 MPa. The trend is confirmed also in different configurations (i.e. different temperature and different roughness surface).

A similar influence on the compression displacement has been obtained also considering the two different types of roughness surface as shown in Figure 7. In particular, with the rough specimens, the obtained compression displacement is higher. It seems that the presence of the surface irregularities increases the compression relaxation. The measure of the roughness, Figure 8, allows to summarize and to confirm the effects examined in the different tests. The roughness measured after the test it is inversely proportional to the compression relaxation. Consequently, with the highest temperature the value of the roughness is the lowest. The trend is confirmed in both the types of examined specimens. Thus, it is possible to affirm that the surface roughness is a key factor for the correct tight of the bolted joint. Indeed, considering a joint connection between a plate in aluminium and a plate of composite (average thickness of each plate equal to 10 mm), with a M12 bolt, and evaluating the loose of interference in the joint equal to 0.02 mm, a tight loose of around 1.5 Nm is obtained.

To further investigate this phenomenon, additional tests have been made on the specimens with the rough surface. In particular, in these last tests, the specimens are loaded to the steady state value of pressure, than the load is removed, and subsequently the load is applied again to the steady state value. The results of these tests are summarized in Figure 10. In this case the trend of the curves does not present the dramatic change of the deformation in the initial phase, see the behaviour observed in the first twelve-twenty four hours in the previous tests. Now the trend is smoother and the displacement seems to follow a linear equation. These results are of great interest if a similar procedure is used in the production process. If during the assembly a tight of the joint is followed by an untight, and then the joint is tighten again, the loss in the tight during the operative life of the joint will be much lower and it can ensure the correct working of the connection.

In order to study in depth the behaviour of the relaxation, an interpolation of the displacement curves has been explored using different formulations. In particular, a logarithmic (Eq. 1) and a power law equation (Eq. 2) have been considered.

$$y = a\ln(x) + b \tag{1}$$

$$y = ax^b \tag{2}$$

$$y = ax + b \tag{3}$$

In Table 2 the interpolation parameters for the different examined cases and for the two considered formulations are reported together with the correlation coefficient R^2. It is interesting to observe as, the test at a temperature of 80°C can be interpolated very well with the logarithmic formulation, while the tests at room temperature are interpolated better with a power law formulation. However, in this second case, the difference with a logarithmic interpolation is very small. In Table 3, the interpolation parameters for the last tests where the load is initially applied and removed are shown. In this case, as discussed above, also a linear interpolation (Eq. 3) has been considered. It is possible to see as, a part for the highest pressure, in the other cases the linear interpolation is the best one in terms of correlation.

5. Conclusions

In the last years, one of the key points for the automotive design is the reduction of pollutant emissions. For this reason, the attention is toward the reduction of the weight of the structures and consequently to the use of innovative material for the automotive sector like the composite. Also the joining technologies has to be reviewed in this direction. Thus it is necessary to know the behaviour of this material under different loading conditions. In this work the relaxation effect on composite materials, due to compression load in a direction perpendicular to the fibre is investigated, with a series of experimental tests. The attention has been focused on the possible loss of tight due to this phenomenon in a bolt connection where at least one part is made in composite. It has been demonstrated as an increase of the temperature of the joint, such as a higher degree of the surface roughness increases the compression loss of the material.

A testing machine has been specifically designed and built in order to make creep compressive tests of composite material laminate in the laminate thickness direction. The testing machine and procedure take into accord the existing ASTM D2990 standard but include some changes that are requested by the finalization to the specific application.

Three different variables, the most influencing, have been explored: temperature (with two different values: +80°C and room temperature), the compressive pressure (with three different values: 30, 40 and 50 MPa) and the surface finishing (two different status: as produced and after a supplementary milling of the rougher surface).

Analysis of the obtained results confirms that temperature and pressure are determining the relaxation trend of the material. Through the interpolation of the experimental curves, a mathematical model of the behaviour of the considered material has been obtained to be used in numerical analysis in the design phase.

Further this study clearly shows that to reduce the possible loss of tight in the joint, also the surface quality of the composite part should be carefully controlled.

Finally we have devised a possible manufacturing strategy in order to reduce the tight loss problem: before to reach the delivery state conditions, the joint and consequently the material should be subjected to a load and unload phase. In this way, the possible relaxation effects put in evidence in the initial hours of work conditions, can be anticipated in the manufacturing phase and avoided (or greatly reduced) in the costumer use phase.

6. References

[1] Raghavan J, Meshii M. Creep of polymer composites. Compos Sci Technol 1997;57:1673-88.

[2] Findley WN, James LS, Onaran K. Creep and relaxation of nonlinear viscoelastic materials. New York: Dover Publications, Inc.; 1976.

[3] Kim KT, McMeeking RM. Power law creep with interface slip and diffusion in a composite material. Mech Mater 1995;20:153-64.

[4] Maksimov RD, Plume E. Long-term creep of hybrid aramid/glass-fiber-reinforced plastics. Mechanics of Composite Materials 2001;37(4):271-280.

[5] Goertzen WK, Kessler MR. Creep behavior of carbon fiber/epoxy matrix composites. Materials Science and Engineering A 2006;421(1-2):217-225.

[6] Abdel-Magid B, Lopez-Anido R, Smith G, Trofka S. Compos Struct 2003;62:247-253.

[7] Scott DW, Lai JS, Zureick AH. Creep behavior of Fiber-Reinforced Polymeric Composites: A review of technical literature. J Reinf Plast Comp 1995;14:588-617.

[8] Maksimov RD, Plume E. Long-term creep of hybrid aramid/glass fiber reinforced plastics. Mech Compos Mater 2001;37(4):271-280.

[9] Scott DW, Zureich A. Compression creep of a pultruded E-glass/vinyl ester composite. Compos Sci Technol 1998;57:1361-1369.

[10] Holmes M, Rahman TA. Creep behavior of glass reinforced plastic box beams. Composites 1980;4:797-802.

[11] Mosallam AS, Bank LC. Creep and recovery of a pultruded FRP frame. In: Advanced Composite Materials in Civil Engineering Structures, ASCE, ed. S. Iyer and R. Sen, 1991, p. 24-35.

[12] Bank LC, Mosallam AS. Creep and failure of a full size fiber reinforced plastic pultruded frame. Compos Eng 1992;2(3):213-227.

[13] Wang K, Young B, Smith ST. Mechanical properties of pultruded carbon fibre-reinforced polymer (CFRP) plates at elevated temperatures. Eng Struct 2011;33:2154-2161.

[14] Kouadri-Boudjelthia A, Imad A, Bouabdallah A, Elmeguenni M. Analysis of the effect of temperature on the creep parameters of composite material. Mat and Design 2009;30:1569-1574.

[15] Guedes RM, Moraisb JJL, Torres Marques A, Cardond AH. Prediction of long-term behaviour of composite materials, Comput Struct 2000;76:183-194.

[16] Guedes RM, Morais JJL, Marques AT, Cardon AH. Prediction of long-term behavior of composite materials. Comput Struct 2000;76:183-194.

[17] Weerth DE, Ortloff CR. Creep considerations in reinforced plastic laminate bolted connections. In: Army symposium on solid mechanics; October 1986. p.137-54.

[18] Pang F, Wang CH. Activation theory for creep of woven composites. Comp Part B 1999;30:613-620.

[19] Chen HS, Kung HK. A hygrothermal sensitivity evaluation on the clamp torque of bolted composite joint. In: 17th Annual technical conference of the American society for composites, October 2002.

[20] Shivakumar KN, Crews JH. Bolt clamp-up relaxation in a graphite/epoxy laminate. NASA TM-83268, Langley Research Center, 1982.

[21] Fox DM. Bolted joint studies in GRP. Massachusetts Institute of Technology thesis, 1984.

[22] Pelletier K, Caccese V, Berube KA. Influence of stress relaxation in hybrid composite metal connections. Report No. UM-MACH-RPT-01-02. Department of Mechanical Engineering, University of Maine, January 2005.

Properties	**Unit**	**Standard**	**Value**
Tensile 0° modulus	GPa	ISO 527-4	61,8
Tensile 90° modulus	GPa	ISO 527-4	61,1
Compr. 0° modulus	GPa	prEN 2850 B2	57,2
Compr. 90° modulus	GPa	prEN 2850 B2	55,5
Poisson's ratio 0°	-	ISO 527-4	0,07
Poisson's ratio 90°	-	ISO 527-4	0,04
In plane shear modulus	GPa	EN 6031	3,83
Tensile 0° strength	MPa	ISO 527-4	1034,1
Tensile 90° strength	MPa	ISO 527-4	930,1
Compr. 0° strength	MPa	prEN 2850 B2	541,7
Compr. 90° strength	MPa	prEN 2850 B2	510,8
In plane shear strength	MPa	EN 6031	86,1
Density	kg/dm^3	-	1,5
Tensile strain 0°	%	ISO 527-4	1,66
Tensile strain 90°	%	ISO 527-4	1,5
ILSS 0°	MPa	ISO 14130/1	52
ILSS 90°	MPa	ISO 14130/1	51,7

Table 1. Properties of the material examined.

Logarithmic interpolation					
Pressure (MPa)	*Temperature (°C)*	*Surface roughness*	*a*	*b*	R^2
30	80°	rough	0.00477	0.01580	0.99
40	80°	rough	0.00413	0.01664	0.95
50	80°	rough	0.00366	0.02830	0.91
30	room	rough	0.00173	0.00613	0.86
40	room	rough	0.00126	0.02243	0.89
50	room	rough	0.00121	0.06110	0.89
Power law interpolation					
Pressure (MPa)	*Temperature (°C)*	Surface roughness	*a*	*b*	R^2
30	80°	rough	0.0164	0.18570	0.80
40	80°	rough	0.01600	0.17830	0.71
50	80°	rough	0.02820	0.10360	0.80
30	room	rough	0.00730	0.14370	0.87
40	room	rough	0.02270	0.04740	0.90
50	room	rough	0.06118	0.01864	0.93

Table 2. Interpolation parameters for the different considered cases.

Pressure (MPa)	*Type of interpolation*	*a*	*b*	R^2
30	logarithmic	0.00131	0.03624	0.90
30	power law	0.03648	0.05206	0.91
30	linear	0.00003	0.03937	0.94
40	logarithmic	0.00093	0.04378	0.88
40	power law	0.04387	0.01991	0.89
40	linear	0.00002	0.04580	0.91
50	logarithmic	0.00144	0.05543	0.90
50	power law	0.05561	0.02375	0.91
50	linear	0.00003	0.05894	0.86

Table 3. Interpolation parameters for the specimens tested after load/unload process at room temperature.

ACCEPTED MANUSCRIPT

Figure captions:

Figure 1. Specimens for the creep compression tests.

Figure 2. Rendering view of the testing machine.

Figure 3. Testing machine.

Figure 4. Example of compression curve displacement as a function of the time. The curves have been obtained at room temperature, with the nominal pressure of 40 MPa and on the rough specimens.

Figure 5. Influence of the temperature on the compression displacement for rough specimens with a pressure of 40 MPa.

Figure 6. Influence of the pressure on the compression displacement for rough specimens at a temperature of 25°C.

Figure 7. Influence of the roughness surface on the compression displacement for specimens at a temperature of 80°C and with a pressure of 40 MPa.

Figure 8. Measurement of the roughness for the two considered types of specimen, before and after the compression test.

Figure 9. Compression displacement after a cycle of load and unload, for the considered different pressure. The considered configuration is at room temperature and with rough specimens.

Figure 1. Specimens for the creep compression tests.

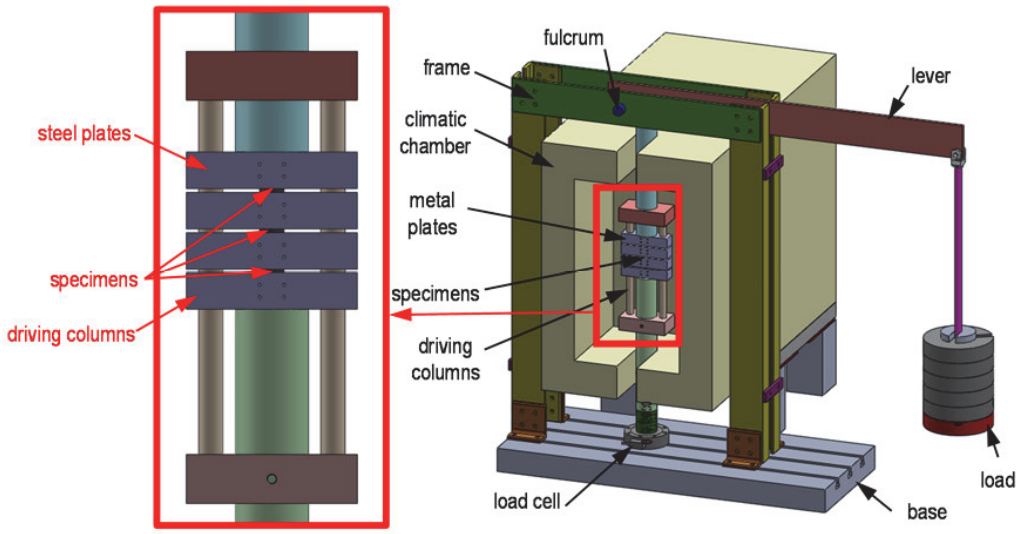


Figure 2. Rendering view of the testing machine.

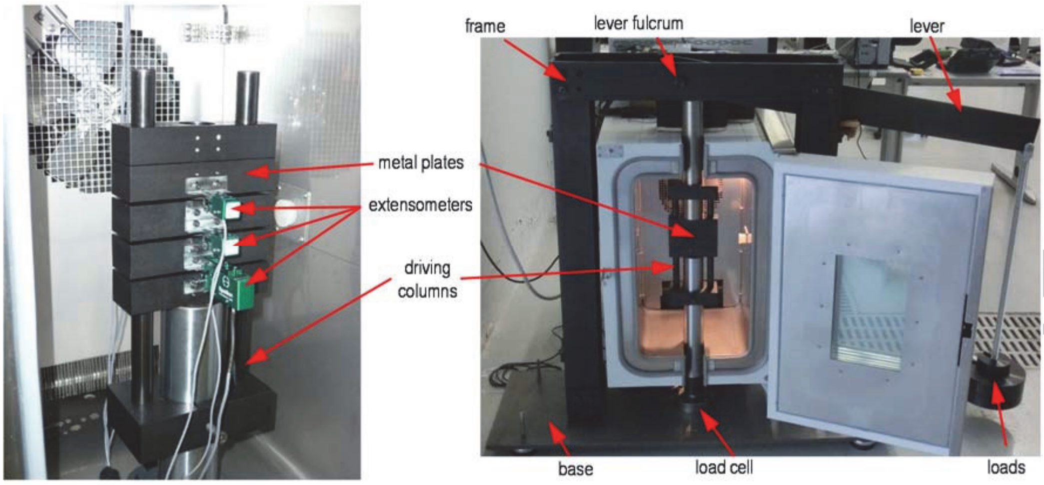


Figure 3. Testing machine.

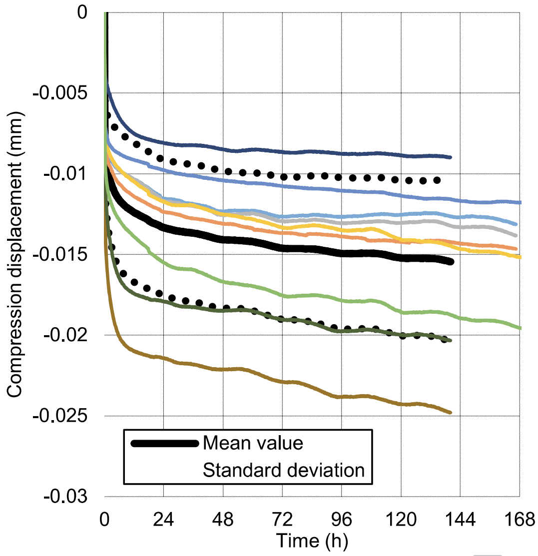


Figure 4. Example of compression curve displacement as a function of the time. The curves have been obtained at room temperature, with the nominal pressure of 40 MPa and on the rough specimens.

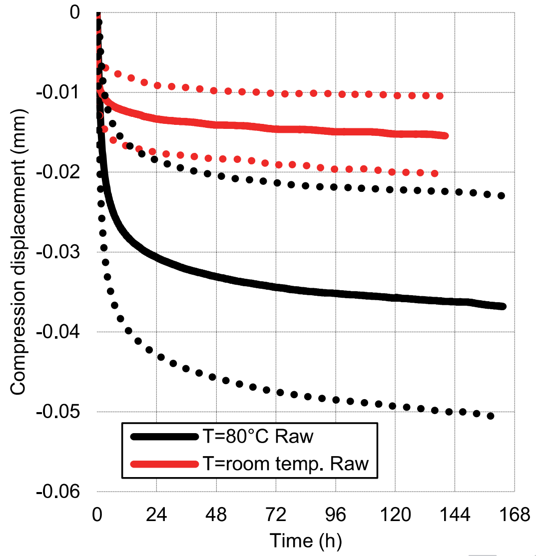


Figure 5. Influence of the temperature on the compression displacement for rough specimens with a pressure of 40 MPa.

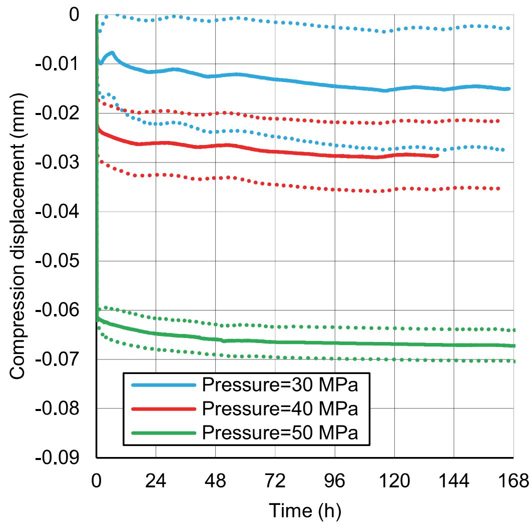


Figure 6. Influence of the pressure on the compression displacement for rough specimens at a temperature of 25°C.

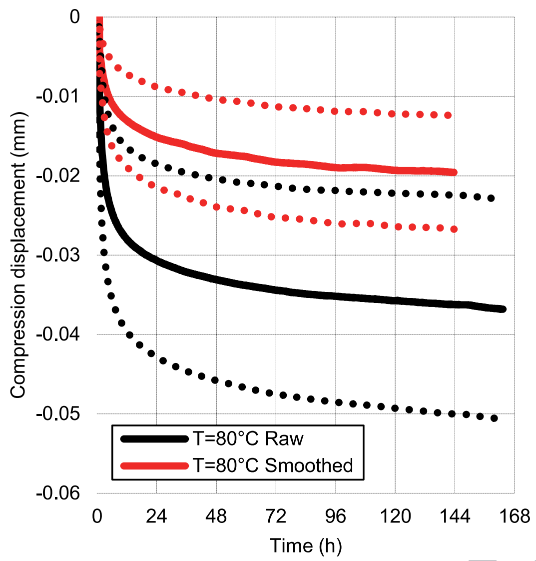


Figure 7. Influence of the roughness surface on the compression displacement for specimens at a temperature of 80°C and with a pressure of 40 MPa.

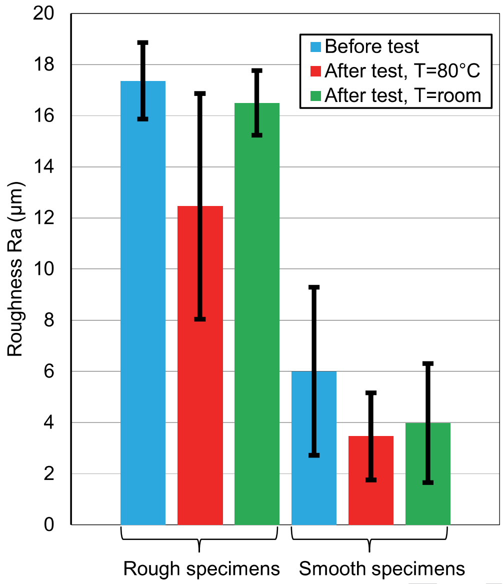


Figure 8. Measurement of the roughness for the two considered types of specimen, before and after the compression test.

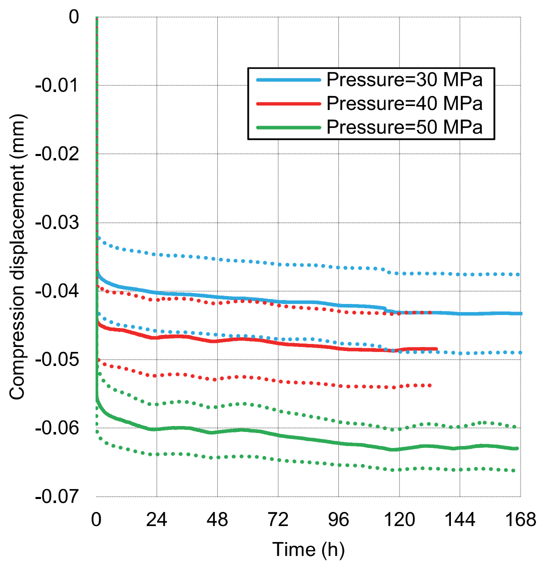


Figure 9. Compression displacement after a cycle of load and unload, for the considered different pressure. The considered configuration is at room temperature and with rough specimens.