Structural use of stacked annealed glass

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Keywords

1=annealed glass 2=friction 3=water

Abstract

Stacked glass sculptures up to 7m high and made up of 700 sheets of 10mm thick annealed glass exploit the strength of glass under compression and combine feats of design and engineering to produce work, breathtaking in its apparent simplicity.

This paper is a result of design development and research carried out by Malishev Wilson Engineers working on two water feature projects, using stacked annealed glass structurally: 7m high glass column in Coventry, UK and nine, 3.5m glass columns in Pompano Park, Florida, USA. The objective was to achieve maximum visual effect and minimum high skills requirements for production and installation of features. The structures involve use of 700 and 350 sheets of 10mm thick glass respectively.

The presence of water and it's subsequent ingress between glass sheets led to serious doubts about shear capacity of the stacked glass if subject to horizontal loadings. To clarify this issue series of tests were carried out at Imperial College London, to ascertain the coefficient of friction for the glass in dry and wet conditions.

This paper also outlines the issue of glass thickness variation and flatness of commercially available glass, using results from research carried out at Imperial College London and elsewhere. It concludes with a summary of calculation results.

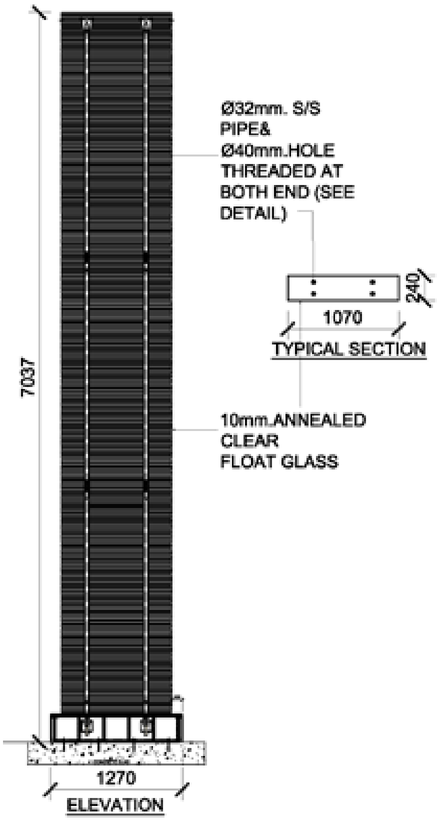

Figure 1 Elevation and Section of the structure

7m high Stacked glass feature, Isle of Capri, Coventry, UK

This project, although unbuilt, gave us an opportunity to explore some of the properties of the glass which are not readily available on the public domain. The "wow feature" in Coventry is a water feature comprised of 700 sheets of 10mm thick stacked glass to create 7m high wall with water flowing over it crating rippling effect. Although in general very similar to the Police memorial glass feature in London's Pall Mall, designed by Lord Norman Forster and build by Haran Glass, the presence of water created a challenge in quantifying structural design, especially shear capacity at the base.

Our initial engineering intuition suggested that the presence of water can only reduce the coefficient of friction between the sheets of the glass, and therefore reduce its capacity to withstand horizontal forces due to internal pressure etc. Actually, the opposite is true! We have discovered with the help of Imperial College London (and our own research) that the presence of water, between the glass actually increases its coefficient of friction.

Fusion Glass Designs Ltd and Malishev Wilson Engineers carried out series of preliminary tests to establish in principal the nature of the problem before more detailed tests are undertaken at Imperial College, London.

Here are some basic details about this test:

Specimens

- 26 specimens were provided, each measuring 190x190x10mm
- Sliding tray, measuring 300x300x10 with a hole for hanging scales
- Two weights, 25kg each

Figure 2 Preliminary testing at Fusion Glass Ltd

Testing equipment

- Hanging scales, 50kg capacity
- Tap water.

Testing regime

One glass specimen 200x200x10 was laid on the timber boards with the sliding tray on top. The tray was loaded in equal increments of 5 sheets each. After each increment pulling load test was carried out.

After all glass specimens were used (25 in total), a weight of 25kg was used to check further effect of the loading applied, see table below.

Table 1 Testing results

Number of plates	Total weight Applied (kg)	Vertical pressure (Mpa)	Pulling Load (kg)	Coefficient of Friction(static)
5	6.75	0.00187	1.5-2	0.22-0.3
10	11.25	0.00312	3-4	0.26-0.35
15	15.75	0.00436	5-6	0.32-0.38
20	20.25	0.0056	5.5-6.5	0.27-0.32
25	24.75	0.00685	8-10	0.32-0.40
equiv 50	50	0.0138	20-22	0.4-0.44
equiv. 75	75	0.021	40-42	0.53-0.56

Findings

1. The test results are in line with the findings of Imperial College tests, i.e. the presence of water between flat sheets of glass increases friction.
2. The value of frictions seems to depend on the weight applied, possibly as a result of thinner layer of water.
3. After just 11 kg weight applied the coefficient of friction was equal to dry conditions.
4. The static coefficient of friction 0.53 was achieved with a pressure of 0.021Mpa (10% of design pressure at the bottom of the stack), therefore it is expected that the coefficient of friction would continue to increase with more weight applied.

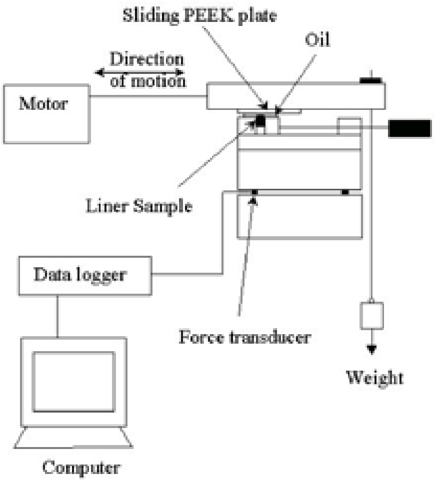

Figure 3 Layout of Experimental Rig

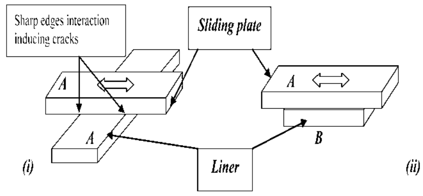

Figure 4 Orientation of speciments

Conclusion

Based on the above data we conclude that the presence of water between the sheets of stacked glass feature will increase the coefficient of friction, depending on the weight applied, and it would be safe, for design purposes, to assume that the value of the frictions would be at least as at dry condition.

Test at Imperial College London

A modified reciprocating rig was used to carry out the experiments. A schematic of the arrangement is shown in Figure 3. The rig simulated the conditions of the glass encounter when a tangential force is applied to two sheets of glass stacked together under the action of their own weight and some external loads. The test rig at Imperial College was powered by an electric DC motor. Rotary motion was converted to reciprocating motion via a gearbox and linear bearing assembly. A slider connected to the linear bearing assembly held various rectangular plates, which were reciprocated on top of a static liner material sample. These rectangular plates were provided by Fusion Glass Designs LTD.

Two force transducers with piezoelectric crystals measured the variation in frictional force. The force was output in the form of variation of electronic units from the Analogue to Digital capture card installed on the computer.

Two sets of specimens were provided by the client:

- A: 41 mm long x 4 mm thick x 13 mm wide
- B: 25.5[1] mm long x 4 mm thick x 13 mm wide

This allowed testing for two experimental configurations as shown in Figure 4. The two alignments were characterized by different contact areas and therefore different average contact pressures, given that the same normal load was applied remotely.

2. Test configurations and different alignments of the samples. (i) Cross vs. (ii) Parallel alignment.

Parameters during the test are shown in table 2 as follows.

Stroke length	11 mm
Slider specimen	A
Liner specimen	A or B
Load on liner from the weight	12.724 [N]
Ambient temperature	Room Temp 19-21 °C
Relative Humidity (RH)	Not monitored
Water	As provided from the tap
Capture rate on A to D card	4000 Hz

Table 2 Parameters for test and other properties

1. Long/Long configuration (i): 1.297kg acting on an area of 13mm x 25.5mm = 38382 N/m^2
2. Long/Short configuration (ii): 1.297kg acting on an area of 13mm x 13mm = 75287 N/m^2

Procedure

The tests were carried out after some experimentation was done in order to find the most suitable and practical means of measuring the friction with the maximum possible accuracy and repeatability.

Dry friction tests were first conducted. They were used as a benchmark for the subsequent tests carried out under wet conditions and for the comparison of the two test configurations (i) and (ii). Configuration (ii) was found to be the best in terms of repeatability and it was therefore used for wet testing. This will be discussed later in the report.

Subsequently the effect of the presence of water in the set up was contemplated. Two different “wet” configurations were then considered:

A. Water was applied to the four side faces of the specimens in order to simulate the presence of water in the interface induced by capillary effect
B. The glass/glass interface was fully flooded before the test was carried out. This was done in order to represent the worst case scenario which could be experienced by the engineers during the structural design of stacked glass sculptures in the presence of undesired misalignments. In this case the water was applied before performing the alignment of the specimens until a consistent water film thickness was achieved.

The final testing procedure can be hence summarized as follows:

Dry samples

1. Ensure that the plated sample sits flush and level with the liner sample.
2. Run the reciprocating rig at low speed to record both static and dynamic friction coefficient during the first few cycles
3. Capture data for a cycle period of 4 seconds at a capture rate of 4000Hz.
4. Repeat steps 1-3 for three sample pairs in order to check for consistency and repeatability.

Wet samples a)

1. Ensure that the plated sample sits flush and level with the liner sample.
2. Flood the side faces of the plates with water.
3. Run the reciprocating rig at low speed to record both static and dynamic friction coefficient during the first few cycles
4. Capture data for a cycle period of 4 seconds at a capture rate of 4000Hz.
5. Repeat steps 1-4 for three sample pairs in order to check for consistency and repeatability.

Wet samples b)

1. Flood the plates interface with water.
2. Ensure that the plated sample sits flush and level with the liner sample and the water is still entrapped between the surfaces so to create a thick lubricating film.
3. Run the reciprocating rig at low speed to record both static and dynamic

friction coefficient during the first few cycles
4. Capture data for a cycle period of 4 seconds at a capture rate of 4000Hz.
5. Repeat steps 1-4 for three sample pairs in order to check for consistency and repeatability.

The raw data captured was then processed by plotting graphs of the variation of the friction with time. The static friction value was recorded at the first loading cycle. The distance between the stable part of the peak and the trough for each curve during the first few cycles was measured from the graph and the dynamic friction coefficient value recorded for each case (see graphs).

Once the raw friction values were available for each run the friction values were converted using the calibration described above and each value tabulated.

Notes on Rig and specimens details

Careful control had to be exercised on repeating the experiments to achieve similar conditions with each test. The main difficulties encountered while setting up the test rig was due to the fact that a perfect alignment should be always guaranteed for flat on flat contact configurations and that the test specimens provided had not been chamfered, this causing undesired edge effects which would contribute to edge cracking and to an unrealistic increase in friction (see Figure 4). This is the reason why the authors abandoned the test configuration (i) after using it under dry conditions. The configuration was abandoned not only because of the alteration of the results induced by edge effects but also because (due to the same reasons) consistent alignment proved to be very difficult to be achieved in this case (see Figures 5a) and b).

Results and Discussion

The final processed data for the entire range of tests carried out is in the form of the evolution of the coefficient of friction with time. Graphical results are reported in (Figures 5-8), whilst a summary of the static and dynamic values of coefficient of friction recorded is reported in Table 3. It should be noted that the static friction was evaluated at the onset to sliding from the first recorded cycle.

Table 3 shows the results for the tests carried out under dry conditions using configuration (ii). Although some edge effect and debris trapping between the surfaces is still present (see Figure 6a)), the results obtained are consistent and show good level of repeatability. As mentioned before, this was not the case for the tests carried out using configuration (i) as shown in Figure 5.

Figure 7 shows results obtained for wet tests following the protocol Wet a). As expected by the authors, the presence of water in the contact interface induced by capillary effect produces friction forces due to the liquid tension of water and a consequent increase of the coefficient of friction with respect to the values obtained for dry contact. However, the unevenness of the trapped water and the formation of a discontinuous thin water layer always generate a friction evolution plot which is very difficult to interpret. As a result, the dynamic friction is highly variable (see Table 3). Furthermore the static value reported in Table 3 for tests 6-8 is bound to be highly dependent on the amount of water trapped and hence might vary greatly depending on the total contact area and edges alignment.

Finally Figure 7 shows the friction coefficient achieved when a sufficiently tick layer of water in entrapped between the glass plates (test protocol Wet b)). Again, the values reported for tests 9-11 might be greatly affected by the water layer thickness and this should be further investigated.

Further work and recommendations

To build up on this work there are a number of areas that can be explored more fully, some of which have already been mentioned. The main areas of interest are:

1. Evaluation of friction forces due to capillary effect and their variation with contact dimensions (scale effects). A thorough investigation of the variation of friction when the film thickness of water entrapped between the glass plates produces high friction forces should be carried out under various loading conditions and using plates of different dimensions. Large scale testing is recommended.
2. Dependence of friction and adhesion forces on the relative humidity (RH). RH is very well known to have a serious effect on the variation of adhesive forces exchanged between surfaces in the presence of water (Bowden and Tabor, 1950). This should be further investigated.
3. Measurement of film thickness for wet contacts and further analysis of the coefficient of friction. Water thickness measurements should be carried out during the tests and curves showing how the coefficient of friction varies with the film thickness produced when adhesion is not a very important issue (hence in the presence of relatively thick water layers) .

[1]Note that the length of the short specimens (type B) was in the range 25-26 mm. This was probably due to difficulties in handling small samples during cutting.

[2]Note that the (?) indicates here the uncertainty of the results induced by edge effects and misalignment problems.

Pompano Park, Florida, USA

This project was a follow up on the stacked glass feature in Coventry. Although the 7m high stack was never built, the research which was carried out for it gave us the advantage of a better understanding of the behavior of stacked glass structures.

The water feature in Pompano is comprised of 9 columns of stacked glass, approximately 3.5m high which support a series of laminated glass surfaces carrying thin layer of water. The water is fed through the central stainless

Test conditions	N.	Coefficient of friction	
		Static	Dynamic
DRY			
Configuration (i)	1	0.4	0.15-0.25 (?)
	2	0.28	0.12-0.19 (?)[2]
Configuration (ii)	3	0.285	0.15
	4	0.305	0.137
	5	0.287	0.145
WET a)			
Configuration (ii)	6	0.544	0.4-0.6
	7	0.5	0.3-0.6
	8	0.576	0.2-0.6
WET b)			
Configuration (ii)	9	0.14	0.1
	10	0.136	0.105
	11	0.138	0.11

Table 3 Experimental results

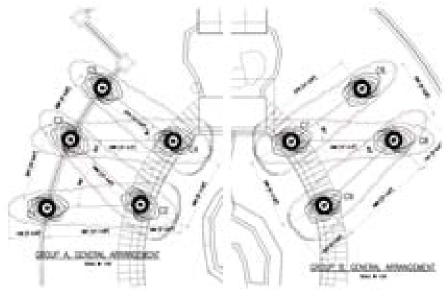

Figure 9 General arrangement drawing

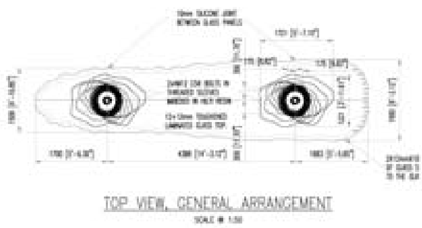

Figure 10 Typical view of the top

steel pipe in the centre of the glass column then spread across the "table top" and discharged at the end of it to the artificial pool at the bottom.

The column is build out of 10mm thick annealed glass sheets shaped as shown above. There were 14 typical sheet sizes used. To create required visual effect each sheet is rotated by 1˚. 55 tonnes of glass was used to build this feature.

One very important aspect of the

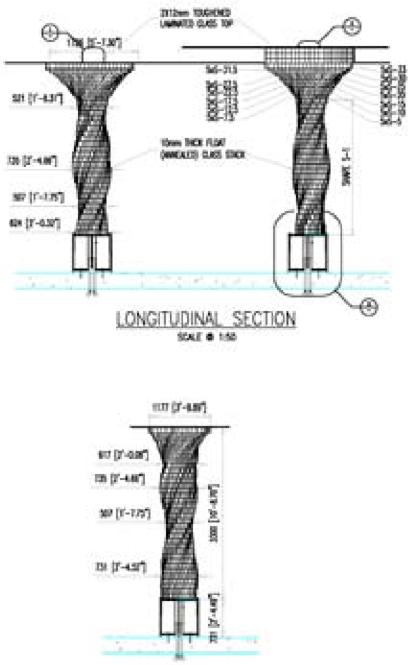

Figure 11 Side & End Elevations

stacked glass features is the variation in glass thickness across the sheet. Due to the fact that stacked glass tends to be quite heavy variations in thickness may create stress concentration in points of contact and cause glass to fail. That is why it is not recommended to use toughened glass for stacked features due to the presence of the roller waves, which create uneven surface.

Despite the fact that every glass producer checks the glass thickness as a routine operation for quality control purposes, we were unable to obtain any concrete data with regards to flatness of a sheet of glass and thickness variations across the width of it. However there is anecdotal evidence that some variation does exist.

After some investigation we chose ultrasonic thickness gauge TT300 supplied by Bowers Metrology group with measuring accuracy of +/-0.01mm.

During our factory visit we carried out tests using a split jumbo sheet of 10mm glass (supplied by St. Gobain). Measurements were taken at intervals of 10cm across the width of the glass sheet. This experiment showed that the glass tends to be 0.35mm thinner along the short edge of the glass. Our measurement proved that the glass thickness becomes consistent at about 250-300mm away from the edge and therefore these edges were trimmed back by the same amount (300mm) and not used in order to avoid unnecessary stress concentrations due to lack of flatness.

Design

The Geometry of the stacked glass column presented a challenge right from the beginning, since the architectural drawings were not descriptive enough to be able to copy their geometry and use it in our analysis. In addition it was suggested that each layer (ply) should have a different shape, which

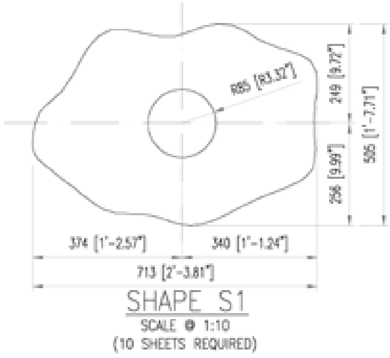

Figure 12 Typical column section at the bottom

immediately produced a knock-on effect on design and production times as well as created budget issues.

Therefore it was proposed that some sort of unification and standardization is required in order bring this feature in line with the original program and budget.

After several attempts, a 3 dimensional solid model was produced

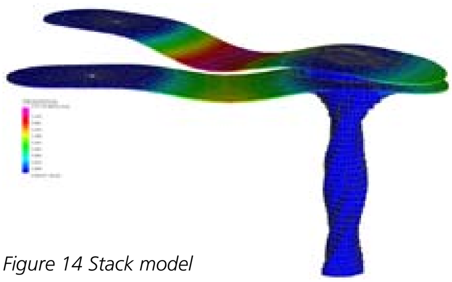

Figure 14 Stack model

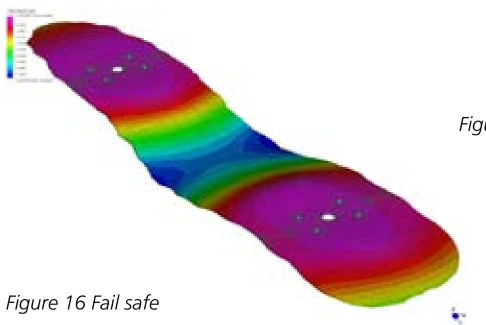

Figure 16 Fail safe

for discussion with the architects, and subsequently approved for further design development.

The solid model was based on the concept of repetition of the same profile of glass but rotated by 1˚ at each layer with exception only at the column head, where larger sheets of glass were used to create the haunch. This produced the required effect of "organic shape" with

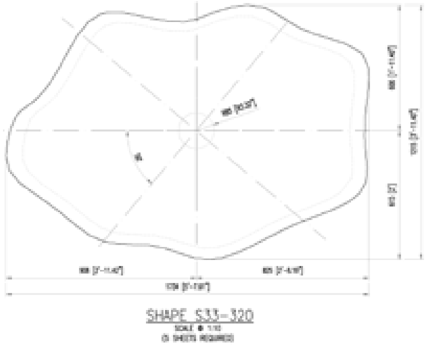

Figure 13 Typical column section at the top

a minimum amount of individual shapes of glass. In the end, only 14 shapes were required to build all the columns, which helped to speed up production considerably.

AutoCAD drawings were produced for those shapes and used as a template for cutting the glass. Overall 3150 pieces of glass were cut, packed and shipped over to Florida in stages.

Strand7,a finite element analysis program, was used to define the stresses and deformations of the glass. Due to the fact that the project is being built in USA and subject to compliance with local codes of practice it is also required to be approved by a locally licensed engineer. Thanks to Front Inc,a façade engineering firm based in New York, this problem was easily overcome and we had our calculations approved by the local authorities. Construction of the project was completed in April 2007.

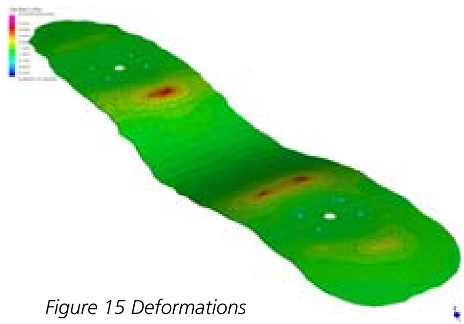

Figure 15 Deformations

Summary of results

- Maximum Summary of the bending stress of the bridging element – 4182psi (allowable 10600psi);
- Maximum stress under fail safe conditions-12879psi (allowable 13500psi);
- Maximum stress in stacked glass – 2064psi (2900psi allowable);
- Maximum deflections at mid-span of the bridging element is 0.32” against allowable of ¾''

Design references

- International Building Code IBC 2003;
- ASCE 7-03 Minimum Design Loads for buildings and structures;
- ASTM E1300-03 Load resistance of glass in buildings;

Acknowledgements

- Dr Daniele Dini and Dr Atul Rana Imperial College London;
- Philip Khalil/Front Inc, New York

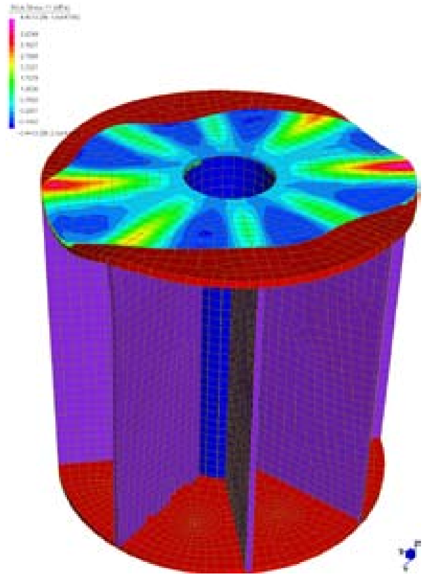

Figure 17 Stresses at the base

Graphs

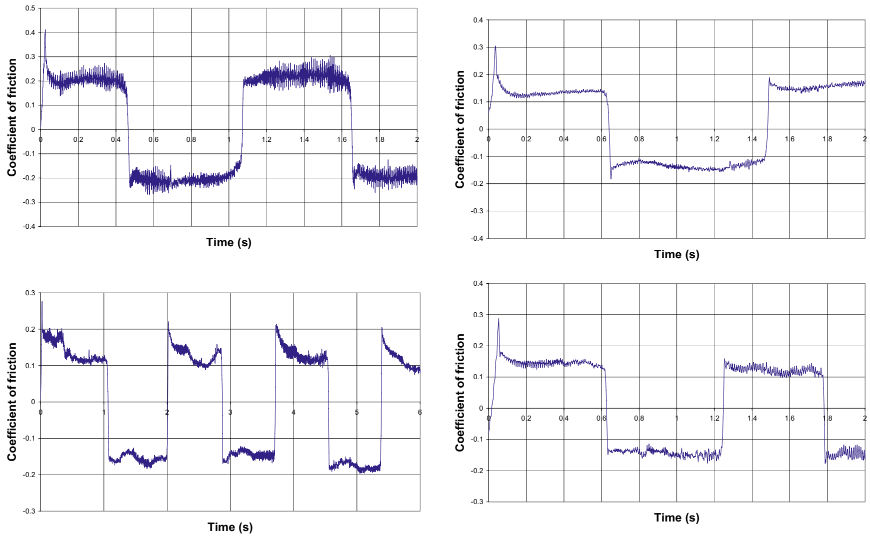

Figure 5 Friction evolution: a) test 1; b) test 2.

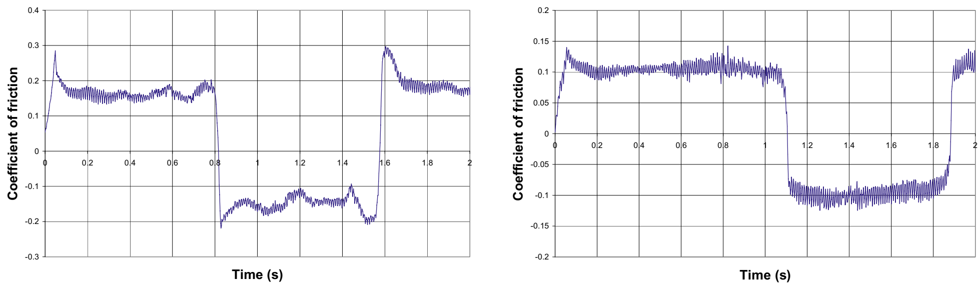

Figure 6 Friction evolution: a) test 3; b) test 4; c) test 5.

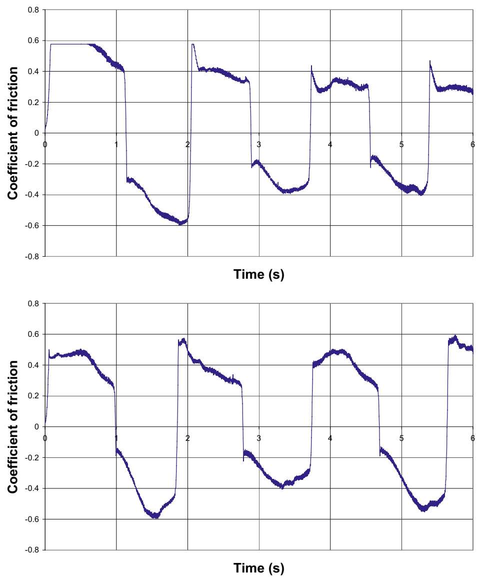

Figure 7 Friction evolution: a) test 6; b) test 7; c) test 8

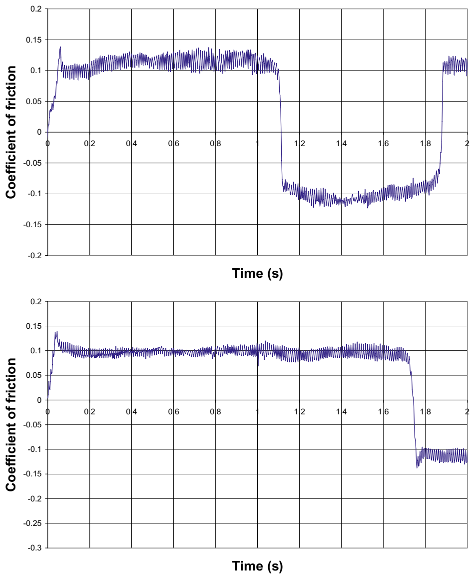

Figure 8 Friction evolution: a) test 9; b) test 10; c) test 11.