EXPERIMENTAL VALIDATION OF THE ESRF UPGRADE PROGRAM EXPERIMENTAL HALL PROTOTYPE SLAB

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Abstract

In 2008, the Council of the European Synchrotron Radiation Facility (ESRF) launched the ESRF Upgrade Programme. One of the key elements of the Upgrade Programme is to produce nano-sized beams. This requires the construction of 120 m and in some cases even longer beamlines. A combination of extended experimental hall and satellite buildings will address this need.

The design of the concrete slab that will host these new beamlines is particularly important. Of course the vibrational stability of the slab is a key aspect in its design. However, hydrostatic levelling system (HLS) measurements indicate that slab curling driven by temperature gradient variations through the slab are an equally important consideration [1].

The tolerances for this new Experimental Hall Extension EX2 slab were expressed in micrometre and nano-radian movements. Builders who are used to working within centimetre tolerances have a difficult time to imagine what micrometer movements and nano-radian tilts on a concrete slab mean. Some effort was required to convert the ESRF design specifications into something that made sense to civil engineers. Finally, a maximum value of 300 µm/m for shrinkage was determined by the prime contractor/design engineering team as one key parameter to meet ESRF criteria.

In early 2012 a prototype slab was built at the ESRF to test the construction procedure for the EX2. Part of this test comprised determining if the expected shrinkage tolerance was respected. In addition slab curling was observed using a dense HLS installation. This paper presents the results of these measurements.

INTRODUCTION

A long ESRF Upgrade Programme nano-focusing beamline can be compared to a microscope. Its primary measure of merit is spatial resolution. The size of the incident X-ray spot -or probe- on the experimental specimen determines this resolution. One of the principal aims of long beamline experiments is to focus the X-ray beam to the smallest possible probe size. When using a single focusing element, which is the case with long beamlines, the size of the focal spot (probe) is limited by the demagnification of the source size and by the diffraction limit (see Figure 1). Expected long beamline probe sizes will range between 20 and 50 nm.

Uncertainties due to translation and rotations on the beamline must be less than 15 µm and 100 nrad over the period of an experiment. This is typically in the order of ½ hour. Uncertainties due to translation and rotation are illustrated in Figure 2 [2].

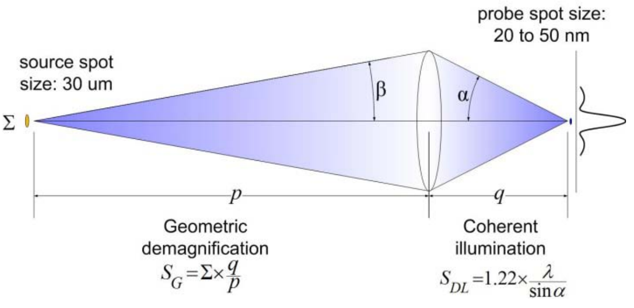


Figure 1: The size of the focused X-ray probe spot size depends on: the source size, the distance between the source and the focusing optics p, and the working distance between optics and the experimental sample q. At the ESRF *p* is nominally 150 m and *q* is in the order of 0.05 m. The demagnification is therefore q/p=3000^{-1} giving a theoretical probe size of 10 nm. Actual probe size is expected to be between 20 and 50 nm.

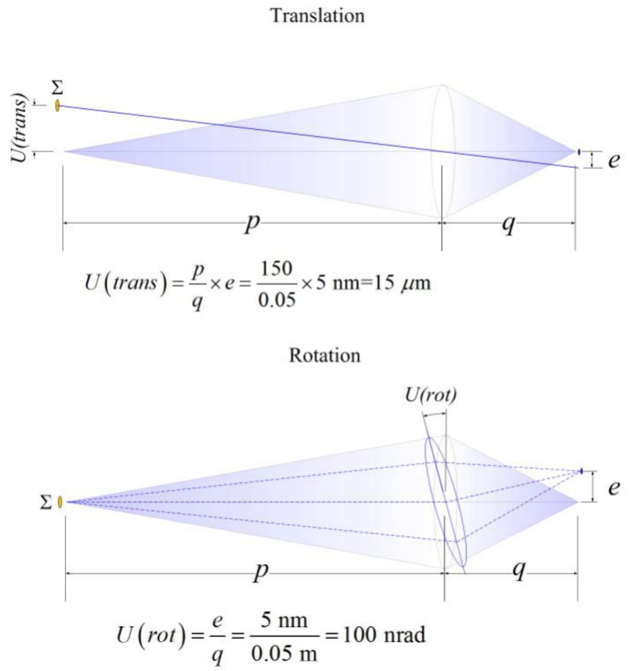


Figure 2: Uncertainty due to translation and rotation errors.

THE ESRF EX2 SLAB DESIGN

The experimental tolerances discussed above have to be translated into design tolerances for the EX2 slab. These tolerances are divided into static and dynamic load cases. Only the static error case loads are discussed here. The static case load error budget components for the EX2 slab are given in Table 1.

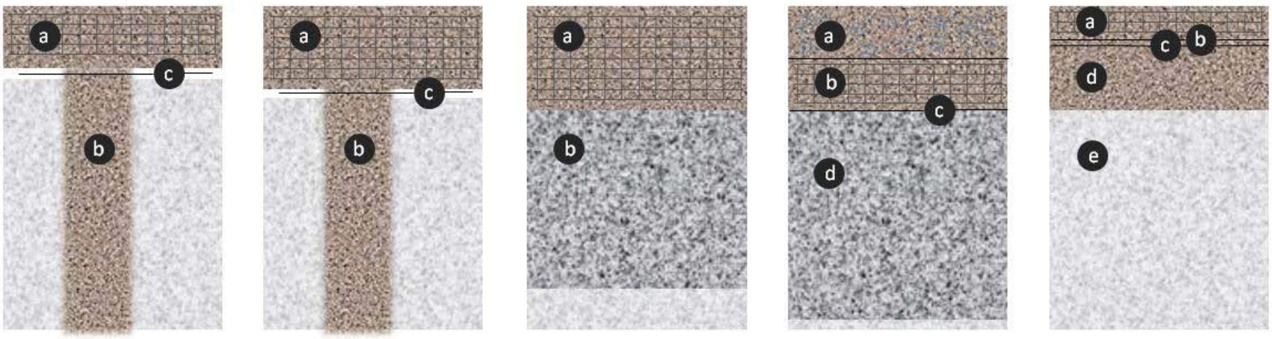
Table 1: The main EX2 static load cases and maximum tolerated deflections.

Load Case	Maximum Deflection
Two pedestrians at 3 m	< 0.5 µm
Two pedestrians at 3 m	< 2.0 µm and < 200 nrad
Temperature over 12 hrs	< 2.0 µm and < 200 nrad
Temperature 20 °C outdoor change	< 1.0 µm and < 100 nrad

Recent designs for several experimental hall slabs were studied. Each design is optimised for the specific site configuration and characteristics. These and the ESRF EX2 design are shown in Figure 3.

The ESRF is located on an old glacial lake bed. This lacustrine clay base is overlaid by alluvial material deposited by the two adjacent Drac and Isere rivers. This underlying base material is relatively homogeneous to significant depth. The ESRF slab design comprises:

- Hard compaction of the underlying base lacustrine/alluvial material.
- A 550 mm thick rollcrete slab (*dry mixture* of gravels, sand, 5% cement and 3%water)
- A 100 mm thick finishing layer (mixture of gravels, sand, 12% cement and 7% water).
- A 2 mm thick bitumen layer which permits the top layer reinforced "golden" slab to slide and accommodate both hydration and long term shrinkage.
- A 350 mm thick steel reinforced quartz finished concrete slab (mixture of gravels, sand, 14% cement, 6% water, additives and 35kg/m² steel).



DIAMOND UK
a) 600 mm Steel reinforced concrete slab
b) 600 mm diameter pile driven to the chalk layer
c) 50 mm space

SOLEIL FRANCE
a) 800 mm Steel reinforced concrete slab
b) 600 mm diameter pile driven to the Fontainbleu sands
c) 50 mm space

ALBA SPAIN
a) 1000 mm Steel reinforced concrete slab
b) 1700 mm compacted stone

PETRA III GERMANY
a) 500 mm fiber reinforced concrete slab
b) 500 mm steel reinforced concrete slab
c) Bitumen layer
d) 2000 mm compacted old concrete

ESRF FRANCE
a) 350 mm steel reinforced concrete slab
b) 2 mm Bitumen layer
c) 100 mm finished concrete layer
d) 550 mm rollcrete layer
e) Compacted earth

Figure 3 Profiles of several recent light source experimental hall slab designs. Each design is optimised for the given site characteristics. The ESRF design is shown on the far right.

SLAB SHRINKAGE AND CURLING

Recall that a maximum value of 300 µm/m for shrinkage was determined by the prime contractor/design engineering team as one key parameter to meet ESRF criteria.

Hydration and hardening of concrete during the first day(s) is critical. The concrete at this age undergoes complex volume changes such as autogenous[*] shrinkage, drying shrinkage and thermal deformation that lead to a rapid build-up of tensile stresses. At the same time strength and stiffness is relatively low, but increasing as the hydration continues. There is a competition within the concrete between the development of tensile stress and the development of strength – both of which are evolving with time. Abnormally fast drying and shrinkage may lead to increased tensile stresses at a time when the concrete has not yet gained sufficient strength. This results in greater shrinkage cracking and a potential for degraded performance.

A good portion (as much as half) of the water added to the concrete mixture will not be part of the hydration products and will not be chemically bound to the solid phase. Accordingly, when the curing period is completed and concrete is subjected to a low relative humidity environment, the resulting gradient acts as a driving force for moisture migration out of the material, and its reduction in volume. Drying shrinkage is the volume reduction that concrete undergoes due to moisture migration when exposed to a lower relative humidity

[*] Autogenous shrinkage is a volume change resulting when there is no moisture transfer to the surrounding environment.

environment than the initial one in its own pore system. Swelling occurs when there is an increase in moisture content due to absorption of water.

A second, simultaneous shrinkage phenomenon occurs. Creep is the time-dependent strain that occurs due to a constant stress. It is the tendency of a solid material to move slowly or deform permanently under the influence of this stress. Its mechanism is called relaxation: the time-dependent reduction of the stress due to a constantly maintained deformation level in time. It occurs as a result of long term exposure to high levels of stress that are below the yield strength of the material.

Simplistically, concrete shrinkages can be divided into two phases. The initial hydration phase (first day-s) followed by long term –typically the lifetime of the slab- shrinkage and creep.

Slab curling is caused by differences in temperature and moisture between the top and the bottom of the slab. The slab edges curl upward when the surface is drier and shrinks more, or is cooler and contracts more than the bottom. Curling is most noticeable at the construction joints but can also occur at saw-cut joints and random cracks.

The curling moment is greater at the ends of the slab decreasing to almost zero at the slab centre. Due to gravity the internal stresses caused by curling are smallest near the slab ends and highest over a large centre area.

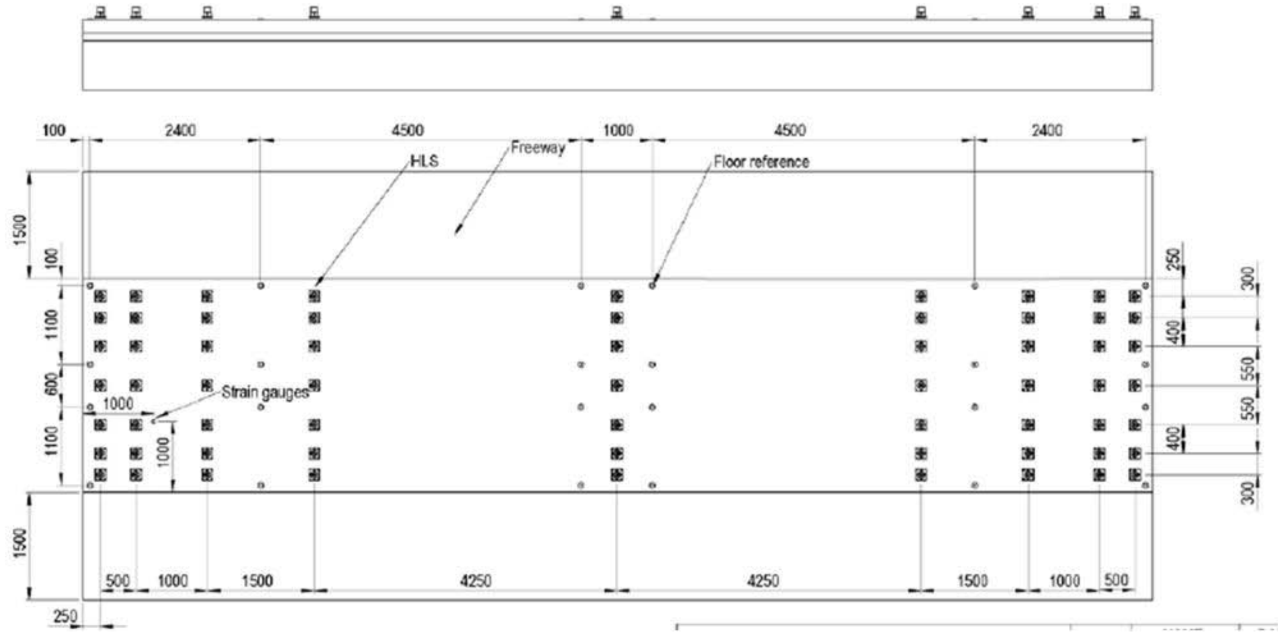


Figure 4 The layout of the reference marks used to measure the slab shrinkage and the HLS used to measure the curling of the EX2 prototype slab.

THE EX2 PROTOTYPE SLAB

The ESRF built a prototype slab to test and validate the full construction process for the EX2 slab according to the design described in the section *The ESRF EX2 Slab Design*. This prototype slab is 15 m long and 3 m wide. Comprehensive measurements were made to characterise both slab shrinkage and curling on this prototype. This section presents the results of these measurement campaigns[†].

It is worth mentioning that there is no visible cracking on the prototype slab.

Shrinkage Measurements

The prototype slab was poured in the morning and finished in the evening of 12 March 2012. A reference network of 24 points was installed on the slab in the morning 13 March. The configuration of this network is shown in Figure 4 and in the photograph in Figure 5.

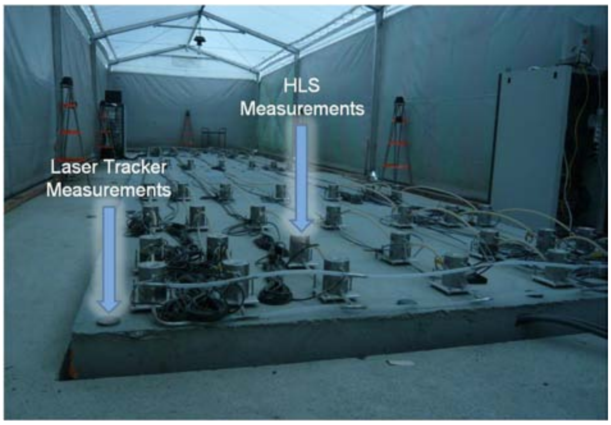


Figure 5 Photo showing the installation of reference marks and HLS on the prototype slab.

[†] Note that slab shrinkage and curling are complex phenomena. Results on the prototype slab are certainly indicative of what will happen on the EX2 slab. However, environmental and size differences will certainly also have important influences.

Horizontal and vertical angle, and distance observations were made from four steel tripods permanently fixed in the walkway adjacent to the slab with a Leica AT401 laser tracker. The three dimensional positions of the reference points were then determined by least squares.

To determine shrinkage, all of the distances (i.e. 276 distances) between the different points were computed and compared to the first series of computed distances measured at 14 hrs on 13 March.

Temperature has a very important influence on the movement of the EX2 prototype slab; and there were large temperature variations - between 8.4 and 32.7 °C - over the study period. To separate the shrinkage – which is what we are really interested in - from the thermal movements of the slab a simple temperature correction model is used. The reference temperature was taken to be 20 °C and all corrections are made to this reference. The temperature model is determined iteratively. First a power model for shrinkage is determined for the measurements. This is the red curve in Figure 6. The differences between the these measurements and the model are calculated and put into a simple straight line regression against the temperature difference with respect to 20 °C. Then a temperature correction based on this straight line model is determined and added to each data point. The whole procedure is repeated substituting the *corrected* measurements for the previous ones until the residuals with respect to the best fit shrinkage model do not change - to within a given tolerance- from one iteration to the next.

Results are shown in Figure 6. The asymptote of the model curve in this graph is less than 180 µm/m.

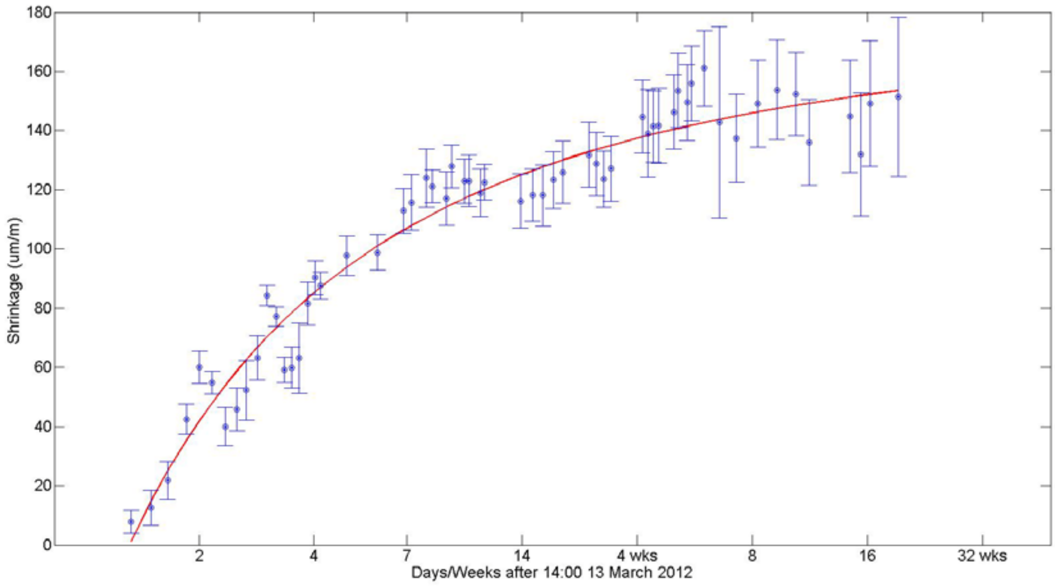


Figure 6 Shrinkage of the EX2 prototype slab over 19 weeks 13 March - 25 July 2012.

The prototype slab was equipped with six strain gauges to determine shrinkage in the slab mass in addition to the shrinkage measurements made on its surface. Figure 7 shows the disposition of the strain gauges in the prototype slab. Figure 8 shows the temperature corrected -to 20 °C- strain gauge readings[‡]. They are directly comparable to those measured on the slab surface and discussed above (see Figure 6). The top graph of Figure 8 shows the six temperature corrected stain gauge readings. The bottom graph shows the mean of the five strain gauges located at the bottom of the reinforced slab, the gauge located at 70 mm depth, and the surface readings and model of Figure 6.

This second graph is interesting in so far as it shows a shrinkage gradient through the slab. The strain gauges at the bottom of the slab show very little shrinkage while the one at 70 mm depth shows a delay or inertia with respect to the surface shrinkage.

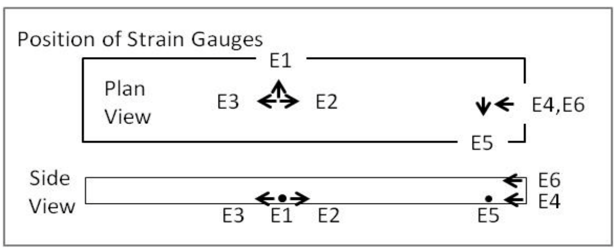
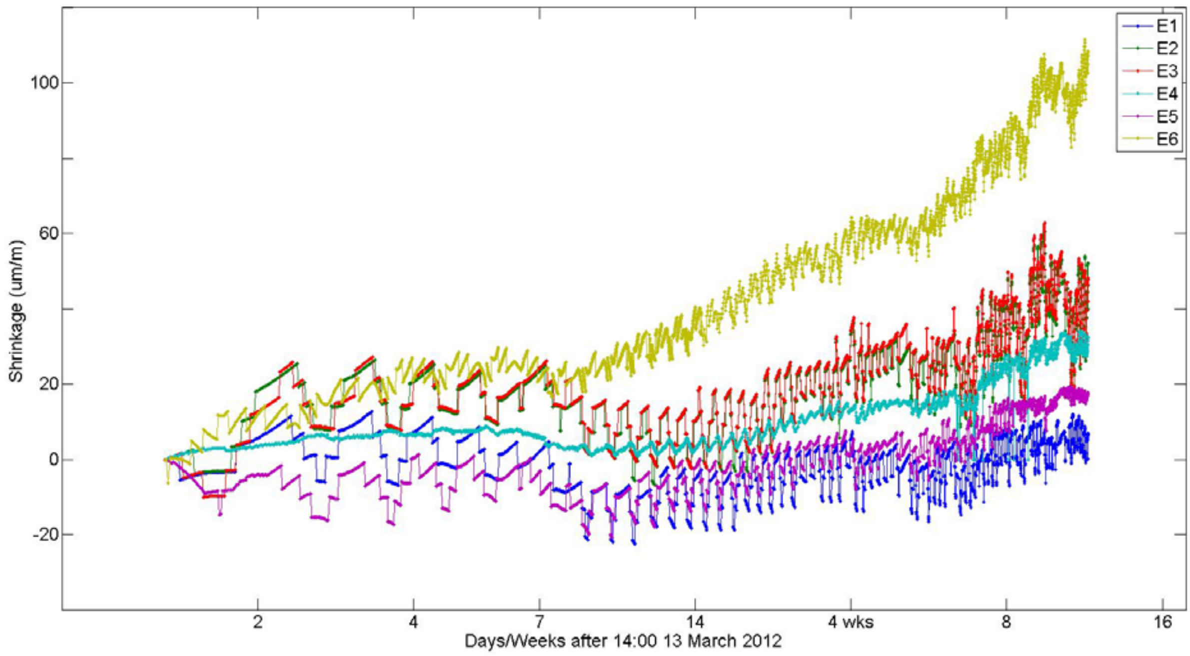


Figure 7 Position of the strain gauges on the prototype slab.

[‡] These data are provided by Mr. R. Schell of Ginger Sechaud Bossuyt, the prime contractor/design engineering team.



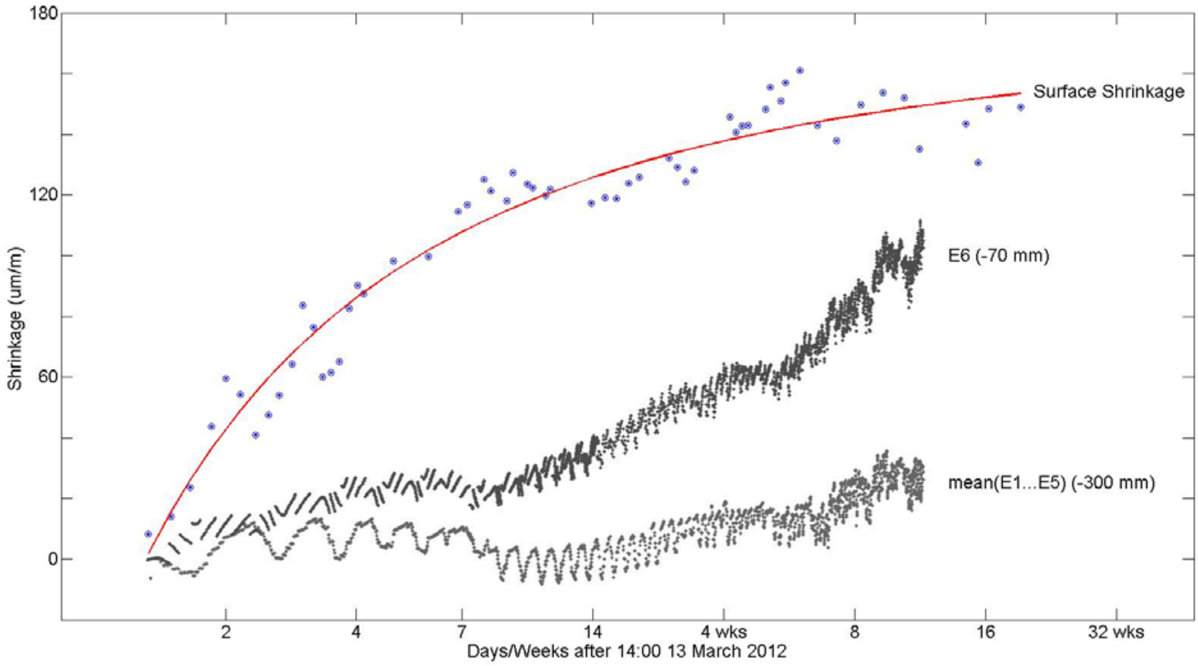


Figure 8 The top graph gives the temperature corrected (to 20 °C) strain gauge readings (see Figure 7 for their disposition). The bottom graph gives the mean value of the five strain gauges at the bottom of the slab, the gauge at 70 mm depth, and the surface shrinkage (Figure 6).

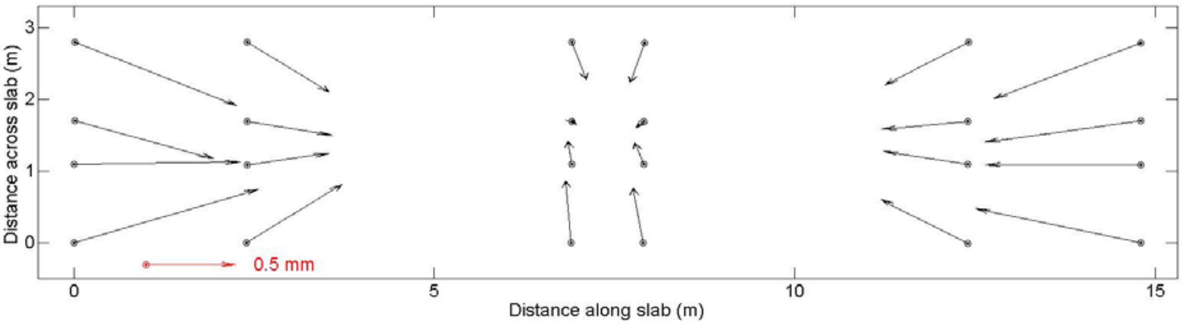
Bitumen Layer

A 2 mm thick bitumen layer installed between the reinforced "golden" slab and the finishing layer is designed to reduce friction and allow the top layer to slide and accommodate both hydration and long term shrinkage. The measurements made on the EX2 prototype slab give an indication of how this layer behaves.

The top graph in Figure 9 shows the total shrinkage – direction and magnitude - measured at the 24 reference points on the prototype slab between 13 March and 27 July 2012. The bottom graph of Figure 9 shows the non-linear part of the total shrinkage. This is the difference between the actual measured magnitude and direction, and what would be expected to be measured from a purely symmetrical shrinkage of the slab.

The standard deviation of the non-linear components of the movements is 0.08 mm in the X direction (i.e. the long edge of the slab) and 0.10 mm in the Y direction. This graph indicates two things. First there is a slight bending of the slab in the middle. This is shown by the non-symmetry in magnitude of the vectors in the middle of the slab in the Y direction. Second the sliding appears to work well in both the X and the Y directions. The vectors contrary to the expected movement (<0.1 mm) at 2 m and 12.5 m indicate slight resistance in the X direction.

a) Total Shrinkage



b) Non-linear shrinkage

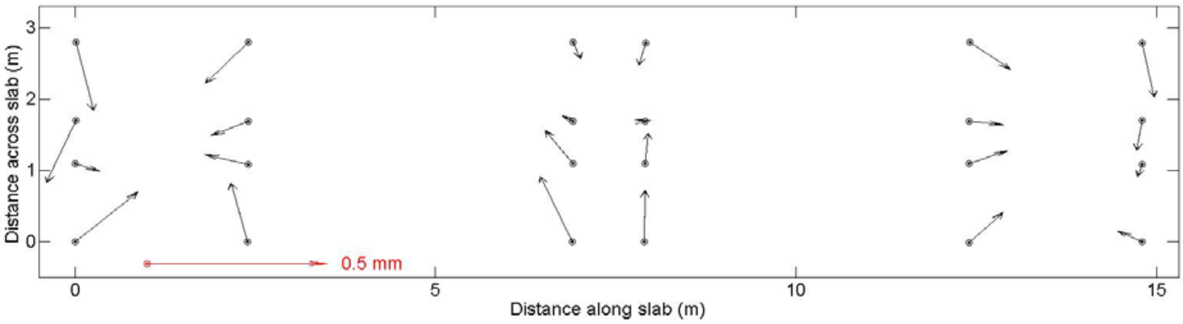


Figure 9 The top graph shows the total shrinkage of the slab measured over the study period. The bottom graph shows the non-linear component of the total shrinkage.

Curling Measurements

There are two main driving mechanisms for slab curling – relative humidity gradients and temperature gradients.

The laser tracker measurements discussed above were used to determine the overall curling. Results are shown in Figure 10. Note these results are not corrected for temperature. Maximum curling at the edges with respect to the centre was 1.98 mm.

Recall there are four lines of six reference marks along the long side (i.e. 15 m) of the slab. Taking each of these lines and subtracting the mean value for the line gives the normalised slab curling shown in Figure 11. Note that because there are only six reference points in a line, it is difficult to predict the *true form* of the model curve. For example it is possible the curling is much more pronounced at the edges of the slab than this model would lead us to believe.

The second main driving force of slab curling is the variation in the temperature gradient through the slab. The design team determined that all things being equal, a thicker slab will curl more than a thinner slab for a given temperature gradient through it. Figure 12 illustrates this effect. Figure 13 shows predicted slab curling due to thermal gradient variations through them.

Figure 14 shows there are large temperature gradient variations through the slab for the illustrative period 23 to 29 March 2012. Variations of this magnitude are not expected in the new EX2. However these measurements are instructive in determining the effect of temperature gradient variation on slab curling.

Figure 15 shows measured slab curling for an air temperature change of +1°C. This graph is derived for the same period temperature measurements are made in Figure 14. Differentiating the modelled curve in Figure 15 gives the tilt along the slab shown in Figure 16. Tilts at the slab edges are large.

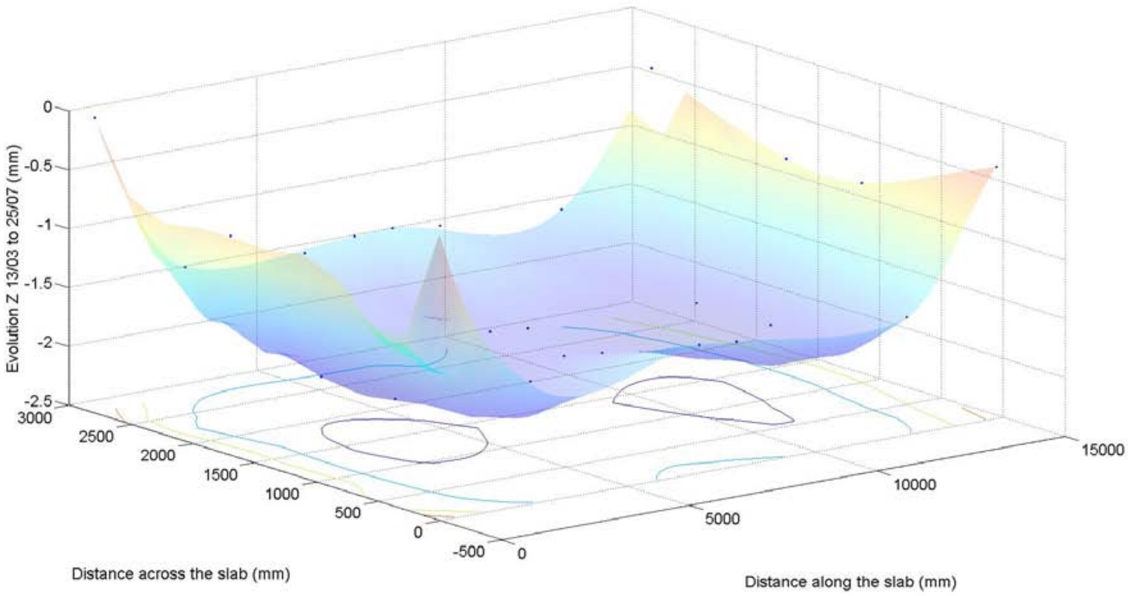


Figure 10 Overall slab bending 13 March to 25 July 2012. Peak to peak curling is 1.98 mm.

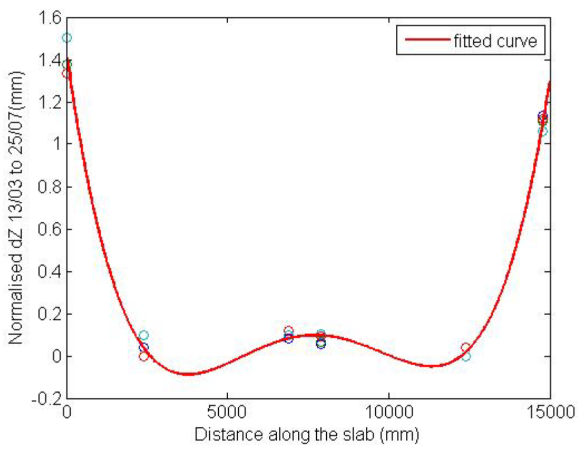


Figure 11 Normalised slab curling. It is interesting the same profile repeats itself across the slab. This behaviour is also seen with the vertical temperature gradient variation induced curling.

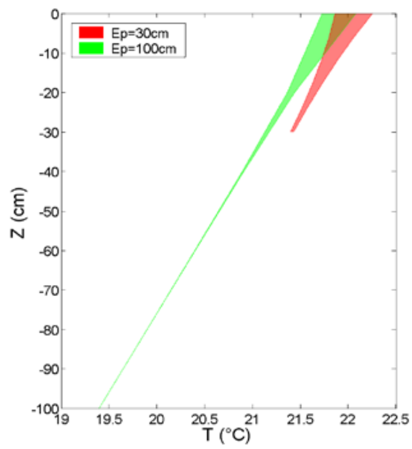


Figure 12 Design model of temperature gradient variation in 300 mm thick slab and in 1000 mm thick slab. Because bending is a function of the magnitude of the gradient, we can see that a thicker slab will bend more than a thin slab for the same gradient. Note the 300 mm slab is offset in temperature for clarity [3].

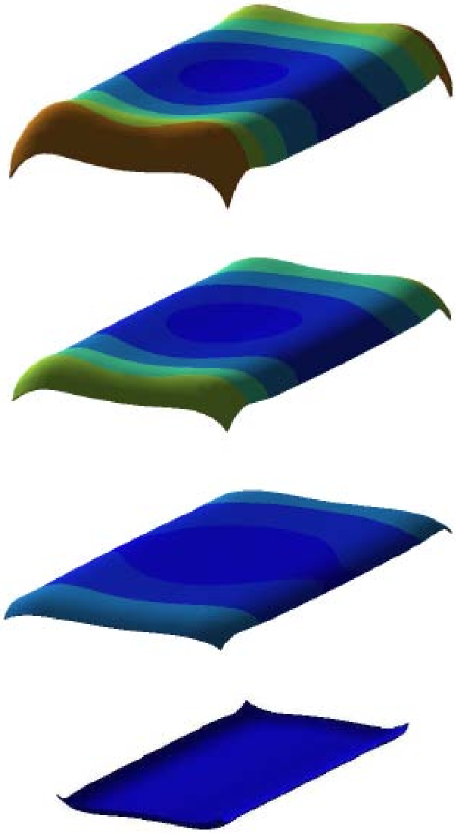


Figure 13: Predicted slab bending as a function of temperature gradient variations through the slab [3].

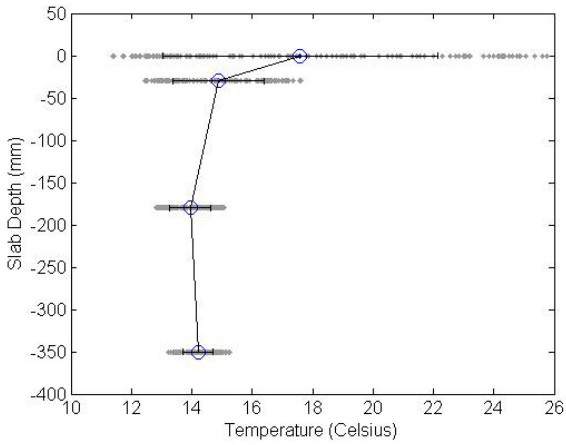


Figure 14: Temperature variation at the surface, and at three levels in the slab over the 144 hour (i.e. 6 day) period between 23 and 29 March 2012.The error bars show ±1 standard deviation.

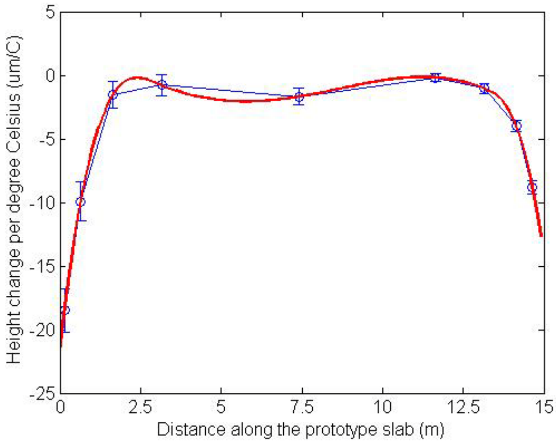


Figure 15: Measured slab curling as a function of air temperature change of +1 °C and position on the slab.

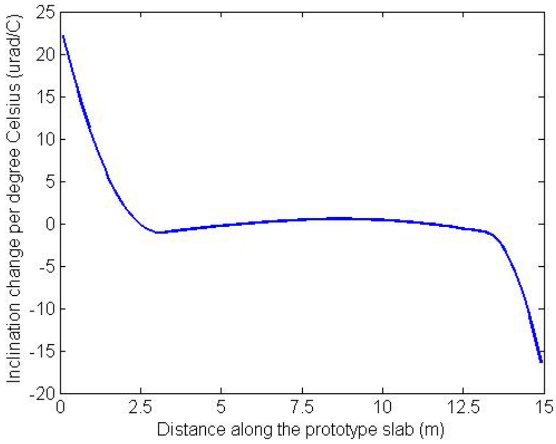


Figure 16: Tilt derived by differentiating the curve in Figure 15.

CONCLUSIONS

The performance of the Upgrade Programme experimental hall EX2 slab is a key element for the new beamlines to be constructed over the next few years at the ESRF. Primarily to validate the construction process, a prototype slab was built in early 2012. A secondary interest was to determine certain parameters that could be indicative of how the EX2 slab might behave. It is understood that due to size and geometry differences, the results presented in this paper are not necessarily representative of the behaviour of the EX2 slab. Because of the edge constraints, this is particularly true of the slab curling.

Uncertainties due to translation and rotations on the Upgrade Programme beamlines must be less than 15 µm and 100 nrad respectively over the period of an experiment which is typically in the order of ½ hour. The design team determined that a maximum value of 300 µm/m for shrinkage is a key parameter to meet ESRF criteria. The measured shrinkage on the prototype slab is estimated to be 180 µm/m. Interpretation of the slab curling results is difficult, particularly at the extreme edges of the prototype slab. Finally, measurements show symmetric shrinkage. This tends to indicate that the bitumen layer appears to be doing what it was designed to do.

ACKNOWLEDGEMENTS

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