Deliberate Deformation of Concrete in the Fresh State
Crack Risk and Efficient Production of Curved Precast Elements

Troian, S; Grunewald, Steffen; Schlangen, Erik; Copuroglu, Oguzhan

DOI
10.1007/978-3-319-59471-2_287

Publication date
2018

Document Version
Final published version

Published in
High Tech Concrete: Where Technology and Engineering Meet

Citation (APA)
Troian, S., Grunewald, S., Schlangen, E., & Copuroglu, O. (2018). Deliberate Deformation of Concrete in the Fresh State: Crack Risk and Efficient Production of Curved Precast Elements. In D. Hordijk, & M. Lukovic (Eds.), *High Tech Concrete: Where Technology and Engineering Meet: Proceedings of the 2017 fib Symposium, held in Maastricht, The Netherlands, June 12–14, 2017* (pp. 2521-2529) https://doi.org/10.1007/978-3-319-59471-2_287

Deliberate Deformation of Concrete in the Fresh State - Crack Risk and Efficient Production of Curved Precast Elements

Sergiu Troian[1(✉)], Steffen Grünewald[2,3], Roel Schipper[2],
Erik Schlangen[4], and Oguzhan Çopuroğlu[4]

[1] Institute of Geology and Seismology, Academy of Sciences of Moldova,
60/3 Gh. Asachi str, 2028 Chişinau, Republic of Moldova
troian.sergiu@gmail.com
[2] Department of Structural and Building Engineering,
Delft University of Technology, Stevinweg 1, 2628 CN Delft, Netherlands
{S.Grunewald,H.R.Schipper}@tudelft.nl
[3] Laboratory Magnel for Concrete Research, Ghent University,
Technologiepark-Zwijnaarde 904, 9052 Ghent, Belgium
[4] Department of Materials and Environment-Microlab,
Delft University of Technology, Stevinweg 1, 2628 CN Delft, Netherlands
{H.E.J.G.Schlangen,O.Copuroglu}@tudelft.nl

Abstract. The production of double-curved precast concrete elements for cladding or shell structures requires expensive CNC (computer numerical control)-milled formwork. As an alternative method, the innovative flexible mould for economically efficient and sustainable production of such elements is discussed in this paper. This method comprises the use of a flexible, CNC-controlled formwork, which is filled with self-compacting concrete. After a short period of thixotropic stabilization in the fresh state, the flexible mould is then deformed into its desired geometry, typically having a strong curvature radius of only a few metres in one or two direction(s). After hardening and de-moulding, the flexible mould can be reused for elements with the same or different curved geometry. The present paper describes the outcomes of a study focussing on two aspects relevant for the abovementioned production method: effect of change of rheological properties in the first 90 min after casting and assessment of the risk of cracking and development of cracks during the deformation process. In an experimental study the following parameters were modified: radius of deformation, moment of deformation in time, panel thickness and water-cement ratio. The presence of cracks after deformation was investigated quantitatively, using a petrographic technology. The results show that for the application of the flexible mould method the plastic stage of concrete is important to be considered.

Keywords: Flexible mould · Self-compacting concrete · Deformation · Cracks · Precast façade panels

D.A. Hordijk and M. Luković (eds.), *High Tech Concrete: Where Technology and Engineering Meet*, DOI 10.1007/978-3-319-59471-2_287

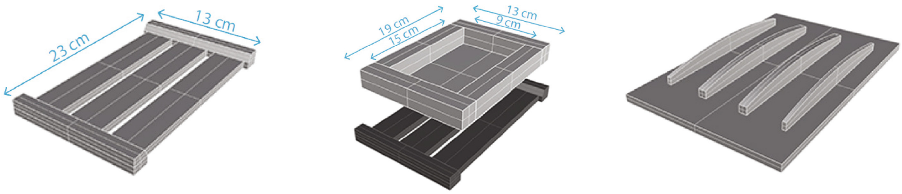
1 Introduction

Several technologies can be applied to produce free-form architecture with double-curved concrete elements. Among the most commonly utilised systems are formworks made of timber, steel or CNC-milled plastic foams which keep the concrete in the desired shape. These technologies come with relatively high formwork costs mainly because of a low repetition-factor of elements used for double-curved structures (Schipper 2015). The first mentioning of a flexible mould system dates back to the 1960's, when the famous architect Renzo Piano (Piano 1969) designed deformed plastic cladding elements, using a pneumatic formwork. Vollers and Rietbergen (2007) describe the development of a computer-driven set of actuators, which can form a curved surface by changing their position on their top. The innovative flexible mould method for economically efficient and sustainable production of prefabricated elements has been further developed at Delft University of Technology and it comprises the use of a flexible, CNC-controlled formwork, which is filled with self-compacting concrete (Schipper 2015). The deformation of the flexible mould has to be executed within an open window of time and two criteria have to be considered: (1) At the moment of deformation the yield stress of the concrete has to be sufficiently high to resist the concrete pressure and (2) it has to be prevented that concrete strain causes a localisation in (larger) cracks (Grünewald et al. 2012). Balance has to be achieved by adequate mix design and production conditioning. The durability of concrete structures depends on the ability of concrete to protect reinforcement, to remain homogenous in the presence of damaging actions like wear, chemical attack or internal pressure. Durability is the capacity of a concrete element or structure to resist weather conditions and environmental impact and it is directly related to the application, exposure conditions, quality of the material, quality of the construction and quality of the design (Chidiac 2009).

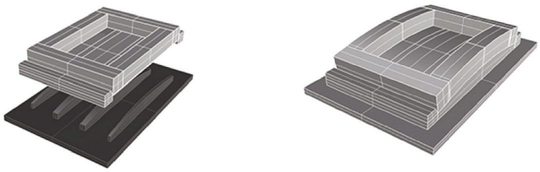
2 Experimental Set-up

The experimental set-up to determine the effect of different parameters on the risk of cracking as a result of the deformation of the mould is discussed in the following. In order to simulate the flexible mould method a simple test system was developed (Troian 2014), which consisted of three main components: (1) the casting surface (Fig. 1a), (2) a flexible mould (Fig. 1b) and (3) the deformation surface (Fig. 1c). Two deformation stages are shown by Figs. 1d and e.

The flexible mould consists of polyether-mattress foam (density 25 kg/m^3) glued to copolyester sheets (Vivak). The inner surfaces of the mould were treated in advance with bi-component silicone rubber P58510 (produced by Poly-Service) in order to avoid direct interaction with cement paste. The aforementioned materials were selected in order to assure proper flexibility. The dimensions of the specimens were 15 cm in length and 9 cm in width, which were selected to allow placing the specimens in the vacuum machine during specimen preparation. The casting and deformation surfaces (Fig. 1) were built from 4 mm thick MDF (Medium-Density Fibreboard)-panels and were cut using a laser cutter, which assured that the shape and dimensions were highly accurate. The flexible mould was fixed during production to the casting surface.



(a) Casting surface (b) Flexible surface (c) Deformation surface



(d) Complete mould (e) Deformed mould

Fig. 1. Mould construction in five different steps.

Four arc-shaped ribs with the required curvature were arranged on the deformation surface. The supports of the deformation surface fit in the openings of the casting surface. The deformation of the mould can be easily and quickly executed by positioning the casting surface and flexible mould on the deformation surface (Fig. 1e). The applied concrete (Table 1) was a self-compacting concrete with a maximum aggregate diameter of 8 mm. With the exception of the variation of the water-cement ratio, the mixture composition was kept constant.

Table 1. Mixture composition for 1 m^3 concrete.

Mixture component	kg/m^3
CEM I 52.5 R	400
Fly ash	160
Superplasticizer	5.04
Water	172
Sand, river 0–4 mm	1045
Coarse aggregates, river, 4–8 mm	563

The mixing sequence for an ordinary free-fall mixer is shown by Table 2.

Table 2. Mixing sequence (total 210 s mixing).

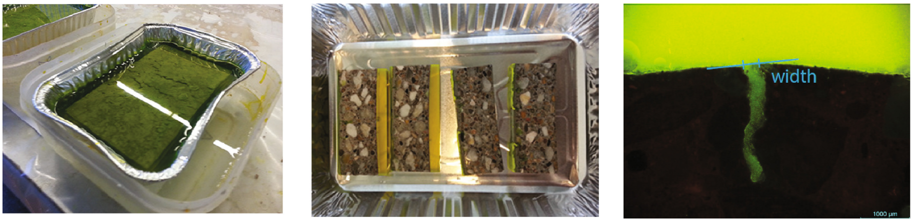
Mixing step	Mixing time
Mixing aggregates + cement + fly ash	30 s
Adding water (90%) & mixing	60 s
Adding water (10%) + superplasticizer & mixing	90 s
Scraping the interior surface of the mixer & mixing	30 s

After a mixture was prepared, it was poured into the casting moulds. Several moulds were used in parallel in order to deform the moulds at different moments after casting. In order to prevent evaporation a plastic foil was placed to cover the cast elements; the plastic foil was not in direct contact with the concrete surface. The test parameters discussed in this paper are shown in Table 3.

Table 3. Test parameters.

Nr.	Variable	Values
1	Radius of deformation	0.25, 0.5 and 1.0 m
2	Panel thickness	25 and 50 mm
3	Deformation time after casting	45, 60, 75 and 90 min
4	Water-cement ratio	0.38, 0.43 and 0.50

In practice, the radii of double-curved/curved concrete elements rarely are lower than 2 m; the radii of deformation in this study were in the range of 0.25−1.0 m in order to study the more extreme cases. After casting, the specimens were left to harden for 7 days under normal room conditions. Then, the specimens were de-moulded and prepared for further investigation (assessment of the microstructure and development of cracks) by epoxy impregnation (Fig. 2). The specimens were placed one by one in a vacuum installation. Under vacuum conditions the elements were impregnated with a mix of liquid epoxy resin and hardener.



(a) Specimen impregnation (b) Sample extraction (c) Measuring crack width

Fig. 2. Test specimen preparation and crack assessment.

The aim of the impregnation process is to fill the micro-cracks and micro-pores with the epoxy mixture, which has a high fluorescence under UV light. After the elements were impregnated, characteristic sections of the specimens were selected and cut; the elements were cut in half using a diamond saw of 3 mm thick, thus forming two very similar, but mirrored, impregnated surfaces. The section surfaces were ground and polished to obtain high quality images. A stereo-microscope was applied to investigate micro-cracking on the top surface of the specimens (magnifications: 6.3x and 12.5x); under the UV light the epoxy-impregnated areas become fluorescent and are clearly visible. More information was gathered from the images through the analysis with the stereo microscope. Each sample was investigated separately and the cracks were counted and measured. It is important to mention that only the cracks formed on the exterior curved surface of the deformed concrete element were inspected, those being the ones most responsible for limiting concrete's service life.

3 Results and Discussion

The presentation and discussion of the results are divided in two parts: (1) effect of deformation on cracking and (2) effect of four parameters on the number of cracks and the crack widths. For each set of test parameters, a single mixture was prepared. One specimen was assessed in the non-deformed state in order to determine whether any cracking occurs due to hardening only. From this test (Fig. 3) it was concluded that no cracks can be observed in the non-deformed state. The effect of four experimental parameters (Table 3) on the presence of cracks is discussed in the following. In this paper, only the number of cracks, the frequency (number of cracks per length unit), the maximum and average crack widths are discussed; a more detailed elaboration of the results is provided by Troian (2014).

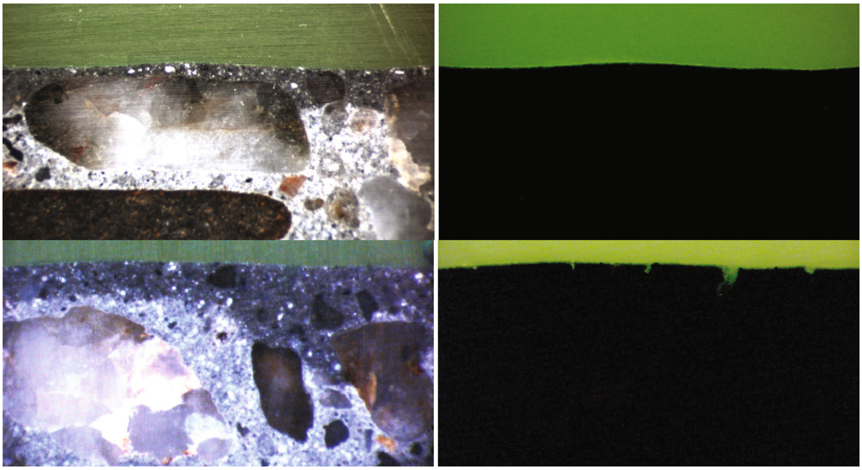


Fig. 3. Assessment of cracking at the surface from parts of a cross-section under normal light (left) and UV light (right): top) non-deformed specimen; without cracks and bottom) deformed specimen (W/C-ratio = 0.50, R = 0.5 m, 75 min after casting); tiny cracks can be observed from the UV light picture.

(1) **Effect of the radius of deformation**
At increasing curvature and with decreasing panel radius the maximum strain of the concrete increases. The total strain is composed of strain of plastically deformed concrete and strain that is located in cracks. In time, the plastic deformability of concrete decreased and more and wider cracks are expected. The results with regard to the effect of the radius of deformation are shown in Fig. 4 for a panel thickness of 25 mm. The frequency is the number of cracks per length unit.

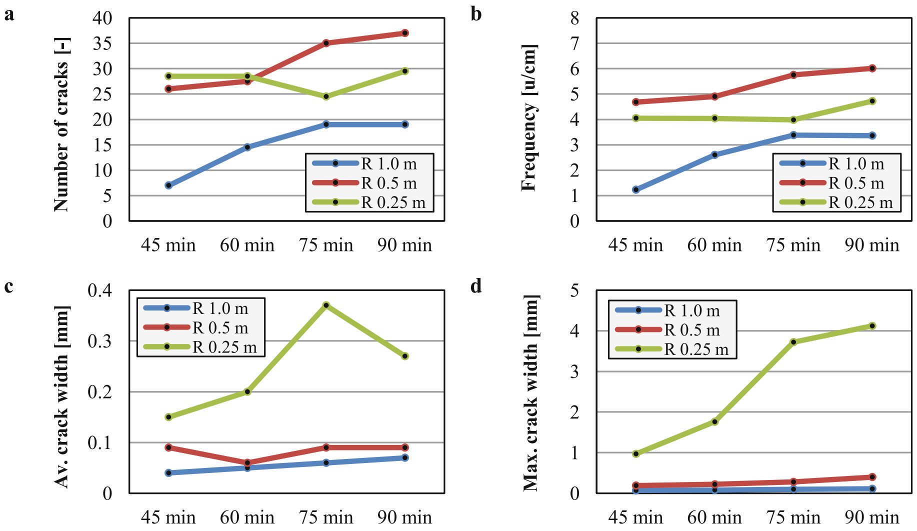


Fig. 4. Effect of curvature (panel thickness: 25 mm): (a) number of cracks, (b) crack frequency, (c) average crack width and (d) maximum crack width.

The radius has an important influence on the number of cracks propagated on the surface of the bend concrete. A high number of cracks and the largest maximum and average cracks widths are obtained for the radius of 0.25 m. The increase of crack widths in time was especially pronounced for the 0.25 m radius, whereas for the radii of 0.5 and 1.0 m the maximum crack widths even after 90 min were smaller than 0.1 mm. Radii of 0.5 and 1.0 m caused very similar outcomes with regard to crack widths.

(2) **Effect of the panel thickness**

Two types of panels having a thickness D of 25 or 50 mm were investigated; the results are presented in Fig. 5. Until 75 min, the panel thickness had a relatively small effect on the number and frequency of cracks formed on the surface of an element. The strain resulting from deformation is larger for thicker panels, this fact is not reflected in the number of cracks; the number of cracks was even slightly higher for the thinner panel. In contrast, larger crack widths were found for the thicker panel which were in most cases significantly larger (in average about twice the crack width). As expected, with a thicker panel wider cracks were obtained, but the number of cracks was comparable or lower.

(3) **Effect of deformation time after casting**

The effect of time already was indicated by Figs. 4 and 5. Figure 6 illustrates the effect of deformation time after casting for a panel thickness of 25 mm and a radius of 1.0 m. An overall increase of the number of cracks in time can be observed. For the period between 45 and 90 min the largest increase was obtained between 60 and 75 min. The average crack width was about constant between 45 and 90 min and the maximum crack width increased gradually in this period.

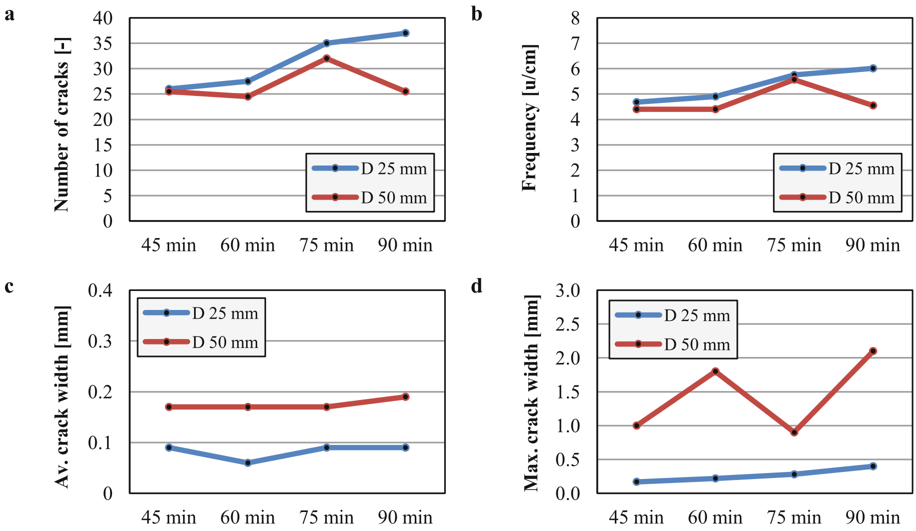


Fig. 5. Effect of panel thickness (radius: 0.5 m): (a) number of cracks, (b) crack frequency, (c) average crack width and (d) maximum crack width.

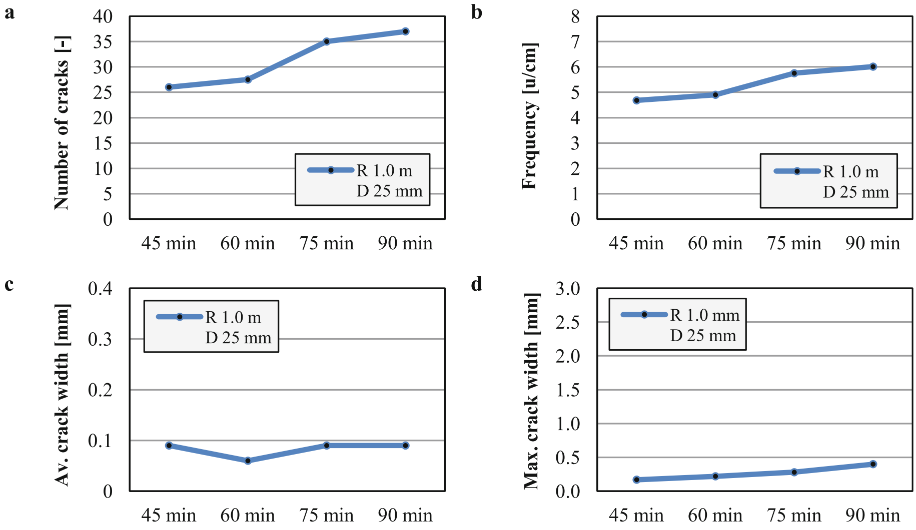


Fig. 6. Effect of deformation time after casting (radius: 1.0 m, panel thickness: 25 mm): (a) number of cracks, (b) crack frequency, (c) average crack width and (d) maximum crack width.

(4) Effect of the water-cement ratio

The effect of the water-cement (W/C) ratio is summarized in Fig. 7. A change of the water content from 0.43 to 0.38 equals 20 kg/m^3 less water for the applied mixture, whereas an increase to 0.50 represents an increase of 28 kg/m^3 in the

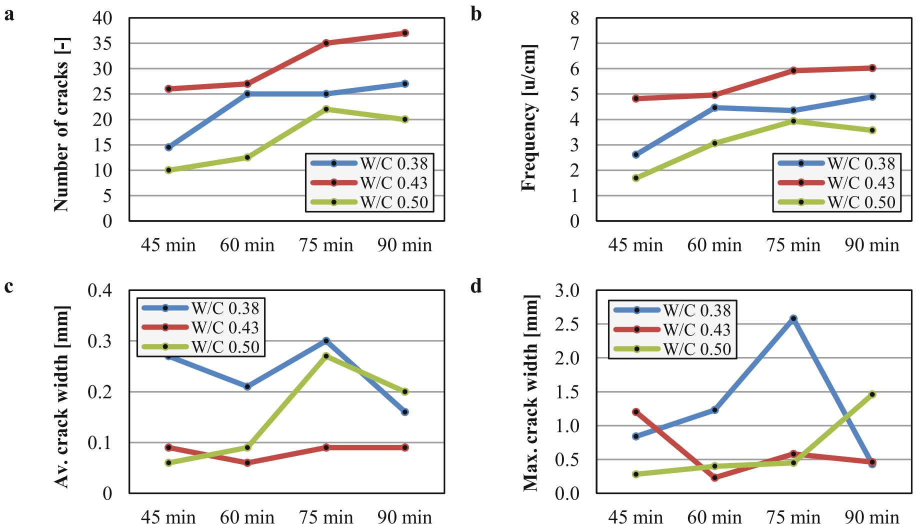


Fig. 7. Effect of the water-cement ratio (radius: 0.5 m, panel thickness: 25 mm): (a) number of cracks, (b) crack frequency, (c) average crack width and (d) maximum crack width.

water dosage. Especially, with the highest water dosage a significant change of the workability was observed with as a result the concrete becoming segregating. At a first view this altered mixture consistency had a positive effect for the mixture containing the highest water dosage (W/C-ratio = 0.50) and a lower number of cracks reflects less pronounced stiffening in time. However, with the more paste-rich composition at the top of the panel the maximum and average cracks widths continued to grow and exceeded those of the mixtures with W/C-ratios of 0.38 and 0.43 after 90 min.

4 Conclusions

The effect of different parameters on the surface cracks of thin panels, deformed in the plastic stage, was discussed. The behaviour of concrete in the plastic stage is time-dependent and the following conclusions can be drawn:

- Dependent on the boundary conditions of deformation, a considerable number of cracks (more or less wide) were observed. The formation of cracks can be counteracted or reduced with an optimized mix design and by deformation at the right moment in time.
- It is recommended to deform panels in a flexible mould system as early as the concrete can support its own pressure preventing it from flowing out of the mould. The load-bearing resistance in this early stage can be enhanced by additional measures like placing a foil on the surface or placing a textile reinforcement.

- A homogenous concrete composition over the height of a panel prevents the formation of larger cracks due to the presence of a paste-rich layer.

References

Chidiac, S.E.: Sustainability of civil engineering structures - durability of concrete. Cem. Concr. Comp. **31**(8), 513–514 (2009)

Grünewald, S., Janssen, B., Schipper, H.R., Vollers, K.J., Walraven, J.C.: Deliberate deformation of concrete after casting. In: Orr, J., Evernden, M., Darby, A., Ibell, T. (eds.) Proceedings of 2nd International Conference on Flexible Formwork, University of Bath, pp. 132–139 (2012)

Piano, R.: Progettazione sperimentale per strutture a guscio – experimental project of shell structures. Casabella **335**, 38–49 (1969)

Schipper, H.R.: Double-curved precast concrete elements: research into technical viability of the flexible mould method, Ph.D.-thesis, Delft University of Technology (2015). ISBN 978-94-6299-154-5, doi:10.4233/uuid:cc231be1-662c-4b1f-a1ca-8be22c0c4177

Troian, S.: Crack evaluation in double-curved concrete elements, Delft University of Technology, Master thesis (2014). http://repository.tudelft.nl

Vollers, K.J., Rietbergen, D.: Adjustable mould for annealing freely curved glass panels. In: Glass Processing Days, pp. 105–107 (2007)