Horizontal Loading Effects of Fresh Concrete on Precast Arches

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Abstract

This paper investigates the horizontal effect of fresh concrete on precast arches. A number of different models of horizontal pressure of fresh concrete are considered in this regard. The effects of fresh concrete on a precast arch are represented as a ratio of maximum normal stress from horizontal action of fresh concrete to the normal stress induced by the self weight of the precast concrete arch. A parameter study on a number of geometric and operational variables has been carried out. The implications of this horizontal loading from fresh concrete have been discussed within the context of the potential financial effects.

Keywords: Arch, Fresh Concrete, Construction, Stress, Design

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INTRODUCTION

Concrete behaves like a Bingham plastic (Wallevik 2006) when placed in its fresh form imparting horizontal pressure onto the support system in place, which may have significant implications for the supporting formwork (Peurifoy and Oberlender 1995). The supporting formwork must be of sufficient strength (Hurst 1983) to withstand this horizontal action that exists until the time when the concrete has hardened sufficiently to be self-supporting (Kovler and Roussel 2011). There exist numerous theories on the variation of horizontal pressure of concrete as a function of the depth of placement pertaining to vertical formwork. These theories all agree that this horizontal action and the resultant pressure is of significant magnitude (Santilli et al. 2010) and through the use of an appropriate pressure model, construction costs related to formwork may be minimized while ensuring safety.

A specific situation considered for the purposes of this paper is the horizontal loading on precast concrete arches by fresh concrete placed in to form hardened in-situ concrete. The situation arises for multi-span arch bridge structures with precast concrete arches with other in-situ elements. An example of such a bridge is presented in Figure 1.

Before the placing of fresh concrete, the precast arches remain simply supported. However, distributions of moments take place and the support conditions change significantly when the in-situ fresh concrete hardens. Consequently, stage-by-stage modeling is often required for design.

A special time window in this regard is when the fresh concrete is placed on the two sides of a precast arch. From a stability point of view, a check is required so that uplift does not take place due to the imbalance of loading in the form of fresh concrete on the two sides of the arch. This problem can be avoided by specifying the difference between the overall heights of each concrete placement on the two sides of the arch to a maximum stipulated value throughout the fresh concrete placement operation. However even under such circumstances, it is possible that significant normal stress is produced in the arch due to the lateral action of fresh concrete acting on the two sides of the arch. This significant normal stress may result in the possible violation of serviceability limit states, such as the control of crack width. Depending on the operation of placement, it is possible for concrete to remain in its fresh state until the completion of this operation. As such, during the design of fresh concrete placement, consideration must be given to the horizontal effects of fresh concrete acting on the structural element to satisfy all limit states, as outlined in Figure 2.

As observed in Figure 2, within the operation of concrete placement, there is a possibility of potential overloading and a compromise with the performance standards. Such a possibility is independent of codes of practices in different countries. Due to the presence of numerous theories for the modeling of horizontal pressure imposed by the fresh concrete and a lack of conclusive experimental data, there exists no consensus on the exact nature and magnitude of lateral loading acting on formwork (Puente et al. 2010). This paper evaluates the aforementioned effects on precast concrete arches employing a number of horizontal pressure theories of fresh concrete. The ratios of maximum normal stress due to horizontal action of the fresh concrete to the normal stress due to the self weight of the arch are outlined and evaluated. The effects of different geometric and operational values are investigated and the eventual potential effects on costs are also discussed.

HORIZONTAL PRESSURE OF FRESH CONCRETE

Significant amount of research has taken place concerning formwork pressure from fresh concrete (Santilli et al. 2011a). These investigations have researched the effects of horizontal pressure of fresh concrete on vertical formwork and the effects of varying parameters on the magnitude of the pressure. Some variability of pressure may be expected when the surface roughness or texture of the surface on which fresh concrete exerts pressure changes (Arslan et al. 2005). In the absence of conclusive experimental results or theories of the effects of horizontal action of fresh concrete on precast arches, envelopes of the existing theories are appropriate for the appreciation of the problem and the associated analyses. In this connection, some engineering pragmatism is required after considering the model-dependent variability of effects.

In this paper, the pure hydrostatic effects of concrete are thus not considered in great detail since a number of existing studies indicate that an approximate linear increase in pressure with depth carries on only to a certain depth. When concrete is left to set for a time, the pressure created deviates from the hydrostatic pressure line and reduces as it is beginning to form an internal structure (Arslan 2002). Also, a quicker curing may be expected to lead to a reduced lateral pressure. With the advance of admixtures, material improvements and need for improved concrete characteristics, there have been advances in concrete properties and performance. One such development is self-consolidating concrete (SCC) which is able to flow and consolidate underneath its own weight by forming an internal structure. A downside of this is that the SCC, when placed, has a lower yield stress and with the plastic viscosity of the concrete there is an increase in the lateral pressure (Kim et al. 2012). Investigations into the effects on the lateral pressure of varying admixtures in SCC have also been conducted (Kim et al. 2010). The properties of SCC mean it can be exploited to produce concrete with a very high workability and/or concrete with a very high strength (Neville 1996). The effects of horizontal loading of fresh concrete acting on formwork can have significant implications for the overall cost of a concrete project (Hanna and Senouci 1997). Considering the absence of data under such circumstances, a number of different horizontal pressure models must be incorporated for such analysis, with varying parameters, to credibly assess the collective effects of horizontal pressure by producing an envelope of individual effects.

MODELS OF HORIZONTAL PRESSURE

Eight different models of horizontal pressure of fresh concrete are initially considered for the purposes of this paper, following existing studies (Santilli et al. 2011b). Of these eight models considered as shown in Table 1, six were chosen for detailed analyses. The hydrostatic pressure model (Equation 1) assumes that the fresh concrete acts hydrostatically with a density of liquid equal to that of concrete, where ρ (kg/m^3) is the bulk unit mass of fresh concrete, g (m/s^2) is the acceleration due to gravity and H (m) is the depth at which the horizontal pressure, P_{max} (kPa), is being considered with respect to the free horizontal surface of the fresh concrete. This model assumes a linear increase in the pressure as the depth of the concrete increases. This pressure model is highly conservative as it does not allow for the concrete to reach a maximum pressure but instead considers the pressure to be constantly increasing until the bottom of the placement is reached. This model has thus not been included for detailed analysis.

The French Standard (NFP 93-350 1995) reports that the formwork must be designed to withstand forces due to the placing of concrete with a density of 2,400 kg/m^3 (Equation 2). The method considers the application of a hydrostatic distribution for formwork design up to 3 m high at which the pressure is at a maximum. The model may be unsuitable for many designs which are over the stipulated formwork height and does not consider effects of the construction process or environment. Consequently, it was decided to exclude this model for the purposes of this paper.

The Gardner model (1980), is based on laboratory studies on formwork (Equation 3), where h_i (m) is the immersed depth of vibrator (minimum 1m), *HP* is the Horsepower of the vibrator, *d* (m) is the minimum formwork dimension in mm, *R* (m/hr) is the rate of placement, *T* (ºC) is the temperature of the concrete and *S* (mm) is the slump after the application of superplasticizer. The model is limited by a maximum of a hydrostatic pressure and considers the bulk unit mass of fresh concrete as 2400 kg/m^3. For formwork design, the power of the vibrator was assumed as 3/4 HP per 305mm of smaller form section. The addition of super plasticizers and extra concrete additives (Gardner 1982, 1984) seems to result in an increase in the mobility of concrete and a decrease in the rate of strength gain at early age, resulting in an increase in pressure.

Adam et al. (1965) proposes a model (Equation 4) based on laboratory test data which is reported to be appropriate for a formwork measuring 3 m in height, 2.5 m in length and varying widths. The model proposes that the loading on the formwork should act as a hydrostatic pressure until it reaches its maximum pressure, after which pressure remains at a constant.

The approach (Equation 5) of E DIN 18218 (2008), a new draft of the German Standard, replaces the previous standard of DIN 18218 (1980), where K_D is a coefficient based on the setting time of the concrete. Included in the standard is a correction factor for concrete of bulk densities other than 25 kN/m^3, a recommendation to reduce P by 3 % for each degree below 15ºC and increase P by 3% for each degree above 15ºC to take into account the constant temperature in the equation.

The Construction Industry Research and Information Association (CIRIA) Report 108 (1978) proposes a model based on a number of large scale field tests and investigations of pressures involved with the formwork (Equation 6). It includes C_1, a coefficient dependent on the size and shape of formwork, C_2, a coefficient dependent on constituent materials of the concrete and K, a temperature coefficient.

The Rodin model (1952) is another experimental model for internally vibrated concrete (Equation 7) where H_{max} (m) is the height at which the maximum pressure occurs. This equation has been found to be valid for a concrete mixture of 1:2:4 (cement : sand : coarse aggregate mass fractions), a unit weight of 2400kg/m^3, a slump of 150mm and a temperature of 21 ºC. Correction factors may be applied for other situations.

The American Concrete Institute (ACI) Committee 347 (2004) considers trapezoidal pressure distribution (Equation 8), where C_w is the unit weight coefficient and C_c is the chemistry coefficient. Although this model is dependent on rate of placement and concrete temperature, the equations may be limited by assumptions of normal internal vibration with vibration immersion of less than 1.2 m, a slump less than 100 mm and the avoidance of admixtures among other things.

Theoretically, the horizontal pressure of fresh concrete has been related to shear strength properties based on soil mechanics principles (Olsen 1968; Alexandridis and Gardner 1981), where internal friction is considered as a basis for shear strength. The lateral pressure theory for soil is also observed in existing literature (Ritchie 1962; Graubner and Proske 2005). Computationally, these are no different in effect than the variation of theories already considered in this paper. Tresca yield criterion (Roussel and Ovarlez 2005), thixotropic considerations (Khayat and Assad 2005a,b), hysteresis loop (Douglas et al. 2005), shear stress necessary for breakdown of concrete (Shaughnessy and Clarke 1988) and many other particulars have often being discussed. The lateral pressure models considered in this section are however sufficient since the envelope of the curve and the understanding of the importance of consideration of horizontal effects of fresh concrete in design is not significantly extended by considering small variations of the fundamental existing models.

Based on the discussions and the scope of the pressure models as presented in this section, the CIRIA model, ACI model, Gardner model, Rodin model, Adam et al. model and E DIN 18218 model of horizontal pressure from fresh concrete are chosen for a more detailed study with respect to their effects on precast concrete arches. Since many parameters are involved with the models and the arch, a baseline case has been established for the purposes of illustration. The baseline case considers the span, the height and the width of a parabolic precast concrete arch to be 15, 3 and 15 m respectively, where the thickness of the arch is 400 mm. The rate of placement of concrete is assumed to be 3 m/h, at a temperature of 20 ^{O}C. The difference between the heights of each placement is kept at a constant of 400 mm, with each placement being alternated between the two sides of the arch and a maximum placement of 800 mm being considered. The slump of concrete is assumed to be 100 mm and the vibrator is assigned a value of 0.75 HP under operation. To determine the effect of the horizontal loading of the fresh concrete acting on the arch, ratio of the maximum normal stress due to the horizontal loading acting on the arch to the normal stress due to the self weight of the arch was determined. Sections were taken along the height of the arch and the normal stress for the self weight and the maximum normal stress from the horizontal loading were found, with the normal stress taken to be acting perpendicular to the section surfaces. Figure 3 displays the arch with baseline conditions following the second placement of the fresh concrete and a section through the arch with the direction of the normal stress is shown.

Figure 4 presents the pressure envelope of the six chosen models with baseline values as described above acting over the height of the arch at a maximum placement of 3 m. All six models presented act as a hydrostatic pressure model until the pressure reaches a maximum. In the cases of CIRIA, ACI, Gardner, Adam et al. and E DIN 18218 the maximum pressure as determined by the respective model, once reached, remains at a constant until the base of the arch. In the case of the Rodin model there is a reduction in the pressure once the maximum pressure is reached. This is explained through experimental data for internal vibration based on which a conclusion was drawn that once the maximum pressure is reached there is a reduction in the pressure experienced by the supporting formwork below the point of maximum pressure. In fact, the CIRIA model does acknowledge this pressure decrease but considers the modeling of the same to be difficult and uncertain, consequently recommending a conservative non-decreasing estimate of pressure after the pressure maximum has been reached following a hydrostatic approach. The model which produces the lowest value of horizontal pressure is the Adam et al. model, while the Gardner model has the maximum value of horizontal pressure for the baseline case considered.

Figure 5 presents the pressure envelope of the six chosen models with varying operational parameters. The values of all other parameters in the models are identical to the baseline case. The rates of placement and temperature's represent minimum and a maximum values chosen around the baseline value. The minimum value of the rate of placement was chosen as 2 m/hr and the maximum as 4 m/hr, while the minimum temperature chosen was 5 ^{O}C, with a maximum of 40 ^{O}C. The Rodin model has been excluded from the temperature dependent pressure envelopes as it does not include temperature as a varying parameter, and as such will remain the same as the baseline model. For all four varying parameters, the Adam et al. model registers the smallest maximum pressure. The increase of the rate of placement parameter increases the pressure acting on the arch significantly. This indicates the importance of the rate of placement as a parameter for all pressure models when examining the effects of horizontal pressure experienced by the arch due to the placement of fresh concrete. The increase of initial temperatures of the fresh concrete also produces significant differences in the pressure acting on the arch during placement. For an initial temperature of 5 °C, only the Adam et al. model reaches its maximum pressure. The CIRIA, ACI, Gardner and E DIN 18218 models do not reach their respective maximum pressure and as a result are hydrostatic in nature. For a temperature of 40 °C all models reach their respective maximum pressures.

Figure 6 presents the pressure envelope of the six chosen models with varying heights of the arch. The values of the parameters for the models were the same as those chosen for the baseline case, with the exception of the height of the arch. For an arch of height 2 m, the Adam et al. model alone reaches its maximum pressure, after which the pressure is constant. The CIRIA, ACI, Gardner, Rodin and E DIN 18218 models do not reach their respective maximum pressures and thus act as a hydrostatic pressure loading. For the arch of height 4m, the Rodin model experiences a significant reduction in pressure once the maximum pressure is reached. The maximum pressure of the CIRIA model records an increase on the baseline value due to its inclusion of the overall height of the formwork as a parameter. The ACI, Gardner, Adam et al. and E DIN 18218 models have a maximum pressure which is identical to the Baseline model. With the increase in height, the pressure exerted on the arch by the fresh concrete for all models is significantly increased and will cause a significant increase in the normal stress ratio experienced by the arch.

EFFECTS OF HORIZONTAL LOADING ON PRECAST CONCRETE ARCH

A number of parameters are chosen in this paper for numerical studies based on finite-element models to illustrate the effects of the horizontal pressure of fresh concrete on a precast arch. This section attempts to investigate the location of maximum stress ratios and to establish an approximate idea regarding the order of magnitude of the stress ratios due to the horizontal action of fresh concrete. The temperature of concrete (*T*), the rate of placement (*R*), the height of the arch (*H*) and the ratio of the dimensions of the precast arch between the span of the arch and the width of the arch (*S* / *W*) were chosen for investigation in this paper, with the values of the parameters for each study listed in Table 2. These parameters were assigned to each of the six models considered for the purposes of a comprehensive investigation into the influence of the parameters on the models, and thus on the normal stress ratio experienced by the arches.

A finite element model of the arch was created using Strand7 finite element software (Strand7, 2005). Eight node hexahedral (Hexa8) brick elements were chosen for modeling purposes. A comparison with sixteen node (Hexa16) and twenty node (Hexa20) brick elements was carried out to ensure the sufficiency of the use of eight node brick elements. The Hexa8 brick model agreed with the Hexa16 and Hexa20 brick models to within 99.2%, with significantly less computing time and thus chosen for arch models. The order of the number of nodes per model was over one hundred and sixty thousand. The loading was applied for different load cases, where each load case represents a different placement of concrete, and range from the arch being empty to the completion of the placement of concrete. The models were then solved using a linear static solver and the solved models analyzed.

The ratio of absolute maximum normal stress due to the horizontal action of fresh concrete to the normal stress for self-weight alone is considered for illustration (Figure 7). The most onerous effects are observed occurring at quarter span.

Figure 7 indicates a similar stress ratio pattern for all models considered in this study along the height of the arch. For all six models, it was the penultimate placement of concrete which produced the highest normal stress ratio, with one side of the arch having the fresh concrete placement completed, to a depth of 3 m, and the opposite side having a fresh concrete depth of 2.8 m. The Adam et al. model produced the lowest stress ratio. This is consistent with the fact that the model produced the smallest maximum pressure as compared to other models considered, as observed in Figure 4. The Gardner model produced the largest stress ratio, with the CIRIA, ACI, Rodin and E DIN 18218 models producing slightly lower stress ratios. The presence of absolute maximum values of the normal stress ratios near quarter spans indicates that this location now becomes an important section for serviceability checks for fresh concrete placements. The maximum stress ratio, as defined in this paper, at the quarter span of the arch is in the region of 4.5.

PARAMETER STUDY

The effects of the change of various parameters affecting the horizontal pressure of fresh concrete and on the normal stress ratios in the arch are considered in this section.

The rate of placement of the concrete is a parameter which can be controlled using a pumping rig onsite. The difference between the different rates of rise values is investigated (Figure 8) ranging from 2 to 4 m/hr, with the baseline having a rate of rise of 3 m/hr (Figure 7). The rate of rise appears to vary the normal stress ratio the least of all the changing parameters analyzed in this paper. It appears that relatively large variations in the rate of rise do not have a significant impact on the stress ratios, ranging from in the region of 4.0 to 4.5. All models exhibit similar patterns of stress ratio. As an easily controlled parameter during construction, the rate of placement of the fresh concrete may be controlled so as to limit the normal stress ratio experienced by the arch.

The influence of temperature is included in the ACI, CIRIA, Adam et al., Gardner and E DIN 18218 models, but is considered constant for the Rodin model. Consequently, the Rodin model was excluded from varying temperature analysis. Three initial temperatures of concrete (5 ^{o}C, 20 ^{o}C and 40 ^{o}C) were considered for this purpose. All models registered a reduction in the normal stress ratio for increasing temperature. The change in the normal stress ratio with variable temperature is more prominent for a change of temperature from 20 ^{o}C to 40 ^{o}C than for a change of temperature from 5 ^{o}C to 20 ^{o}C. Keeping the temperature of concrete below 20 ^{o}C was observed to change the stress ratios very little. The variability of stress ratios within different models is also greater for higher temperatures. The CIRIA, ACI, Gardner, and E DIN 18218 all have equal stress ratios for $T = 5$ ^{o}C, as all the models do not achieve their respective maximum pressures and are fully hydrostatic in nature. The Adam model creates the lowest value of stress ratios as the model achieves its maximum pressure and is thus less conservative than the other models considered.

Changes in geometric properties produce the largest changes in terms of the normal stress ratio. To investigate the impact of changes in geometry on the normal stress ratio, heights were chosen below and above the baseline arch height. Figure 10 illustrates the ratio of normal stress acting along the height of the arch for arches of 2 m and 4 m in height. The lowest height chosen was a 2m high arch, which produced the lowest normal stress ratio for all parameters considered when sections taken through the arch along the height of the arch were analyzed. The CIRIA, ACI, Rodin, Gardner and E DIN 18218 models all showed identical values as their maximum pressures were not reached and all five models were fully hydrostatic in nature under these circumstances. The Adam et al.

model alone reached a maximum pressure in this case but did not produce any notable difference in the normal stress ratio when compared to the other models. For an arch of 4m height, there is a substantial increase and variability in the normal stress ratios. Additionally, for an increased height the variability of stress ratios among different pressure models are more significant than those observed from changing rates of placement or the initial temperature of the fresh concrete. All models show similar stress ratio patterns, with the Gardner model producing the largest normal stress ratio. The Adam et al. model is significantly lower than the other five models, as it proposes that the horizontal action from fresh concrete is more limited than suggested by other models.

The final parameter chosen for analysis was the ratio of the arch plan dimensions. A ratio of the span of the arch to the width of 2 : 1, the baseline ratio of 1 : 1 and a ratio of 1 : 2 were considered in this regard. The varying of the arch geometry produced the second largest normal stress ratios of all variable parameters considered for the purposes of this paper. The difference in normal stress ratios between the span to width ratio of 2 : 1 and the baseline ratio of 1 : 1 was found to be small. This proved significantly different for the plan dimension ratio of 1 : 2, which produced a very high value for the normal stress ratio (Figure 11). This indicates that it is the span of the arch which has a more significant influence on the normal stress ratio experienced by the arch than the width of the arch. For the arch of ratio 2 : 1, the CIRIA, ACI, Rodin, Gardner and E DIN 18218 again produce similar values, with all models indicating a slight reduction in the normal stress ratio from the baseline. For the arch of ratio 1 : 2, all models show a significant increase in the normal stress ratio, with the CIRIA, ACI, Rodin, Gardner and E DIN

18218 models indicating similar results and the Adam et al. model producing the lowest stress ratio. The largest ratio was obtained from the Gardner model.

DISCUSSION ON COST IMPLICATIONS

The horizontal pressure of fresh concrete has direct implications on overall construction costs. While the length of the span and the width of the arch for a particular project is usually predetermined by geometric and site conditions, the thickness of the arch is dependent on the lateral pressure of fresh concrete poured onto the arch during construction. The thickness of arch can be influenced by horizontal pressure of fresh concrete even in the presence of significant reinforcement. Under-designing the arch by underestimating the effects of the lateral pressures associated with fresh concrete may result in failure in the serviceability limit state. This may result in replacing the precast arch after manufacture, adding significant costs to the project. If the problem is noticed after the hardening of concrete, the structure then represents a compromised limit state situation. Conversely, overestimation of the effects of lateral pressures will result in an unnecessarily oversized arch, which will also increase costs of construction.

Through the use of a model arch with baseline dimensions and characteristics as previously described in this paper, the costs of precast arches with varying thicknesses in relation to the overall construction costs was established. The values were obtained for the currently existing rates quoted in the Republic of Ireland. If overdesign occurs by the overestimation of the effects of the horizontal pressure of fresh concrete, costs will be increased unnecessarily through the use of excessively large arch. It was found that by increasing the thickness of the arch from 200 mm to 400 mm can increase construction costs of the bridge by 14%. Conversely, if the stress caused by the horizontal action of the fresh concrete is not designed for and the arch is undersized, a larger replacement arch would be required leading to large and unnecessary increase in costs of up to 40%.

CONCLUSIONS

This paper demonstrates that the horizontal pressure of fresh concrete can have a significant effect on the design and construction of precast arch bridges. The effects were quantified in this paper through the ratios of absolute maximum normal stress due to horizontal action of fresh concrete and that due to self-weight. A number of horizontal pressure theories were considered for fresh concrete and the stress ratios were computed to demonstrate the significant effects of such horizontal action. The quarter span of the simply supported arches were found to be the location of maximum stress ratio values independent of the geometry, material and operational factors. This location is recommended to be checked for serviceability criteria considering horizontal action of fresh concrete.

When conclusive field tests are lacking, a stress envelope generated from different horizontal pressure models for fresh concrete is recommended for use. Although, certain geometric and operational conditions may produce stress ratio envelopes of relative insignificance, this variation can be quite significant for many other conditions. All models considered produced stress effects of the same order under similar input parameters.

Parameter studies revealed that the variation in stress ratios is chiefly guided by the geometric proportions of the arch. When the geometric proportions are under control, the higher temperatures of concrete seem to have a significant effects on the stress ratios. The effect of temperature on stress ratios were observed to be of less significance below 20^{o}C. Rate of placement of concrete does not appear to have a significant effect on stress ratios.

Horizontal effects of fresh concrete have direct cost implications. By ignoring this action, serviceability limits may be violated and the replacement of a structure through redesign would incur additional costs. An overdesign will result in ignoring the pressure model envelope and carrying out approximate calculations using a hydrostatic model will also lead to incurring additional costs.

Acknowledgements

Pat Murphy Quantity Surveyor services.

Oran Precast ltd.

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