

Applied design of UHPC slabs: We need more than compressive strength

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Abstract

Hi-Con has produced precast ultra high-performance concrete (UHPC) elements since 2001, working exclusively with the material. This has resulted in the production of over 100,000 tons of slender UHPC elements. All elements produced, are designed in-house. As such we have a great deal of experience with the boundaries of UHPC design within the architectural codes. The reinforced UHPC slabs that comprise the core part of Hi-Con production, are mainly used for balconies and external walkways. These parts of the structure are most often, only covered directly by harmonized standards with regards to their required carrying loads. Most serviceability limit state requirements (long-term deflection, vibrational comfort) are not directly covered. As such, many references would fall back to the regular guidelines for structural members. These guidelines however, were not set with either secondary structures, or UHPC in mind. This leads to design requirements that are either too lax or even impossibly restrictive. Further complicating the design, is the fact that the design limits are human-induced and/or -perceived.

Keywords: UHPC Design, UHPC walkways, SLS-criteria, Vibrational comfort, UHPC balconies

1. Introduction

For more than 20 years, UHPC elements have been a part of the Danish main-stream construction business. However due to the niche nature of the material, no major standards have yet been changed to reflect this. As such there are deviations and interpretations to the design guidelines, that are necessary to maintain well designed UHPC elements. This article will shortly touch upon the driving design limits and depict references that were designed to them. As a concluding remark, a short note will be given to which material parameters could most effectively be improved to achieve thinner UHPC slabs.

2. Design Criteria and References

When designing elements for the Danish construction market, there are different design criteria to consider. These will be derived from the Eurocode (EC) norm-set, a harmonized technical standard, that is to be applied for structures designed within the European Union. These will then be modified by the Danish National annexes, a set of deviations and additions to the EC, which are to be applied when used in Denmark. In the initial phases of building, a certified structural engineer, will work out a detailed report, describing which of the design limit are to be used as is, and if any limits are further restricted (e.g. lower deflection, higher load) – or if any new ones are added.

This process caters to the individual, however most reports are largely akin to those of the last project. This reliable output can be paired with Hi-Cons extensive design-experience, and a short list of relevant design-driving criteria can be formed: Ultimate limit state (ULS), Long-term deflection (LT-def.) and vibrational comfort.

Design Constrained by Ultimate Limit State

To prove the load carrying in ULS, EC has specified a set of load combinations, however for the design cases calculated and referred to in this paper, this will be either 2,5 or 3 kN/m²(52 or 63 psf), further amplified by a safety coefficient of 1.5. The capacity is likewise estimated from characteristic (5% quantile) parameters, further scaled down by material safety factors that vary depending on material and application.

A recent project done by Hi-Con, was defined by the ULS capacity. The 45 mm (1,8 in) elements to the right span between steel profiles hanging outside a 15 story building, that is currently under construction in Copenhagen, Denmark. These slender elements are designed for a span of 2,0 meters (6,6 ft.). This leaves a bit of design capacity, however, naturally reinforcement can be altered to accommodate this.

While UHPC has enormous capabilities regarding strength, often, the most economical design will include a moderate amount of reinforcement. The ULS bending stress for this slab, ends up being 9 MPa (1.3 KSI),. For reference, cross-sections with large amounts of reinforcement have been designed for 50 MPa (7.2 KSI) of bending stress.

Design Constrained by Long-Term Deflection

In a different example, 60-80 mm (2.4-3.1 in) balconies were designed for a cluster of 4 story apartment buildings. These slabs are supported in 5-7 points and were all designed with the long-term deflection as the constraining factor.

The long-term deflection is calculated via any reliable method, e.g. Bernoulli-Euler theory or finite element method. For the long-term deflection, the live load is included with factor for the part of it assumed to be quasi-permanent. In the case of housing in Denmark, this is 20%. The calculation

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of the long-term deflection, is lastly scaled with two factors, one to account for any reduced cross-section from cracking, and one to account for creep. The creep is a factor that varies depending on the maturity of the element at the time of loading. Historically, this factor translates well when applied to UHPC design. The cracking factor, is dependent on the uniaxial tension stress of the UHPC, however as this factor is intended for use on regular concrete design, the degradation of stiffness in the supplied model is harsh. A better guide for UHPC might be using a higher limit of proportionality. It often means that any designs with UHPC, will have a maximum stress from eigenweight plus 20% of live load just above the uniaxial tension stress.



The calculated deflection must not exceed a set limit that is given by either the certified engineer or the maximum limit suggested in EC – length/250. This limit is simply too lax – and is surely set with hidden away concrete beams in mind. Most end users will complain at a visible deflection of the balcony, and the issue is exposed even further when placed against tilework facades, that have parallel grouting-lines. As such, this upper limit is often ignored in design, and assumed to be approximately half of the given parameter.

Design Constrained by Vibrational Comfort

Long spans, as the ones needed in the picture in the bottom left, were needed for this project in Odense, Denmark. Two span lengths were in this project; 4.3 meters (14.3 ft) and 6.5 meters (21.4 ft). These were solved with 120 mm (4.7 in) and 150 mm (5.9 in) slabs respectively. In order to traverse the 6.5 meter span, elements were cast in 2 and 3 sections, utilizing the negative moment over supports. This solution resulted in elements up to 17,4 meters (57 ft) in length. In the center walkways simply supported slabs span 4.3 meters. For both design cases, a careful evaluation of the vibrational comfort was necessary. Both span widths act as a combination of walkway and as a covered outdoor leisure area.

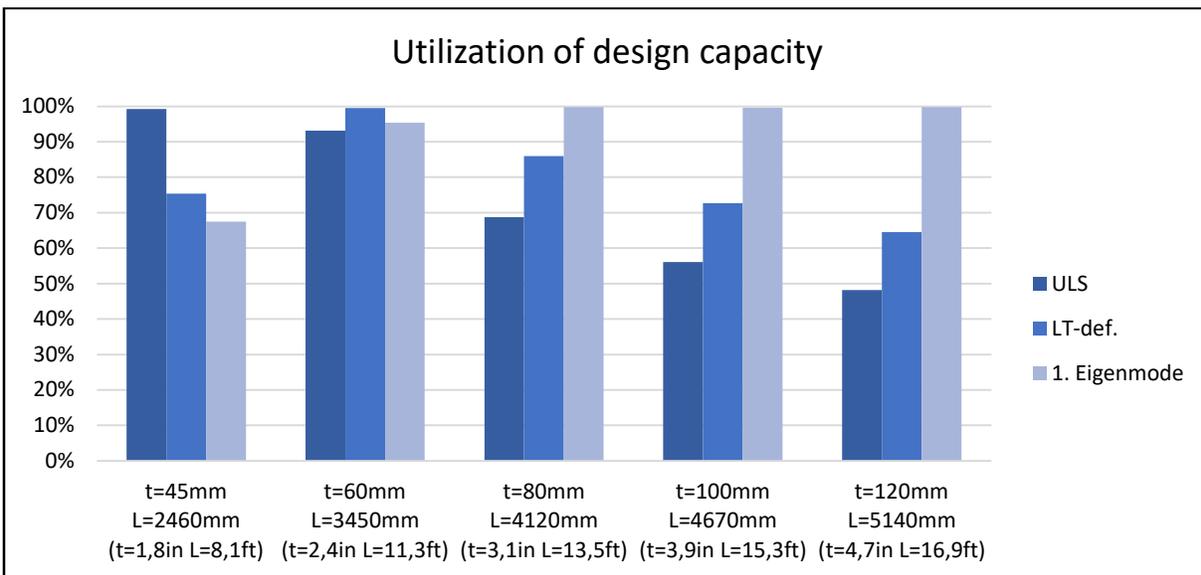


Designing these longer spanning slabs, is often done using the Danish annex to EC 0. This standard, that applies on a national level, sets out recommended requirements for the standard

deviation of the mass acceleration during a passing made following a modal mass model that is described in the same model. Unfortunately, the only relevant limit that has been given is for habitats. This limit is suggested to be 0.01 m/s^2 (0.03 ft/s^2) which suggests a system with average stays of many hours – unlike a walkway. Also, unlike a slab supporting a habitat, the co-accelerated mass is relatively low, as the width of walkways and balconies is often around 1.5 meters. As a result, this simple walkway would have to be tripled in thickness if this criteria was to be met. Further disincentivizing this method is the labor-heavy calculation/simulation required to reach result. Luckily the standard also suggests limits, stating that elements with eigenfrequencies above 8 Hz “often leads to satisfying comfort”. As such this simplified design-limit is most often used and accepted by all. Unfortunately, this does not allow the true potential of UHPC to shine through, as it would have done if a more acceptable limit was available – akin to the 0.35 m/s^2 (1.15 ft/s^2) suggested by the American Institute of Steel Construction for outdoor walkways.

3. Comparative Study

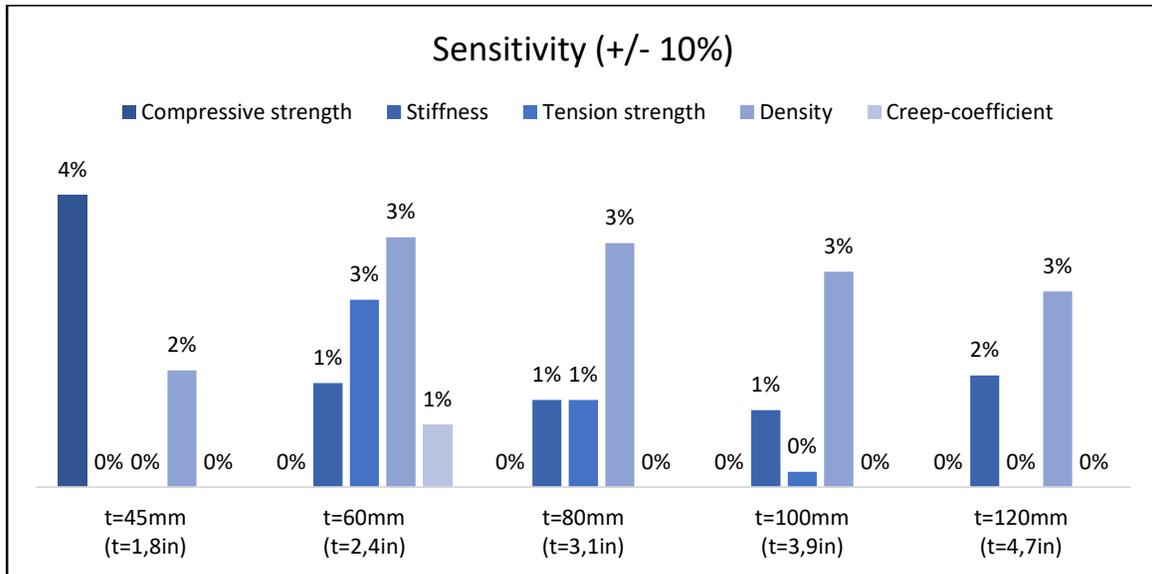
A short study of 5 slabs with a simple span has been conducted. Within this simplified design frame, a 0.7% longitudinal relative reinforcement area has been set. The rest of the relevant design-factors, have been taken from a balcony design case – as described in section 2 of this article.



It can be seen from the applied designs, that only in the thinnest of the reinforced slabs, is the load bearing capacity the limiting factor. This then gradually shifts to being constrained by the long-term deflection. The influence of this criteria should be exacerbated, as the required limit sometimes is twice of what might seem acceptable to the end user. Moving further up in span-width, then means going into designs driven by keeping the eigenfrequency above 8 Hz.

It is important to note that these simplified driving design factors only apply to this exact use-case and with no further added loads. Real designs always complicate things. It can however be used to understand these general systems.

Following the 5 designed slabs, a sensitivity-study has been made. This study measures the relative increase in span-width from a beneficial 10% change in the parameter. It is understood that these changes are not necessarily equally feasible to reach.



4. Conclusion

From the depicted designs, it can be seen that the designer of UHPC elements needs to be vary and not blindly follow given instructions – even when given in a national standard. Depending on the span and thickness of a slab different criteria dictate the design, as such, a designer should mind them all. It can be seen that especially the serviceability limit states are design driving. These can be complex to design by, as the given limits may be somewhat misguided, and the results subjective to the end user.

It can be seen from the sensitivity study that while many UHPCs declare compressive strength, it is rarely the driving factor when designing slabs. Much more focus could be pointed towards lowering the density, or improving the stiffness – as these parameters would increase the volume of the design space to a greater degree.

5. References

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