CROSS: Concern over modelling of concrete-frame building for construction stage

This month we summarise a CROSS Safety Report highlighting concerns around modelling and design checks. This report was submitted to, and processed by, CROSS-UK, but the contents will also be of interest to readers internationally.

Overview

A reinforced concrete-framed building was several storeys in height and supported by a critical transfer slab at first floor. It became apparent that the design had not appropriately considered the construction sequence of the frame.

Report

A reporter's firm had recently been involved in undertaking a peer review of another consulting engineer's design for a reinforced concrete flat-slab frame. The frame was several storeys in height and supported by a critical transfer slab at first floor.

In undertaking the review, it became apparent that the original design had not appropriately considered the construction sequence of the frame. The designer had undertaken their reinforcement design for the critical first-floor transfer slab using a 'global' or 'whole building' 3D design model.

The design model assumed that the complete building structure was *in situ* and fully cured. As such, the analysis gave loads on the transfer slab much reduced compared to that of a conventional 'hand' load takedown, or indeed what would be replicated by undertaking individual slab design models.

The analysis showed loads in columns supported by the transfer slab were only about one third of those that would be obtained from a conventional load takedown. It was clear that the global model had generated alternative load paths within the structure by 'hanging' of columns above the transfer structure; the columns being hung from frames above, proportionate to the frame stiffness, through a catenary or other action.

It is the opinion of the reporter's firm that generation of alleviating load paths was not possible at least when considering the self-weight of the structure. The structure above the transfer slab would either not have been constructed, or would not have sufficiently cured, to provide the stiffness required for such an effect to occur. This is clearly significant when considering a concrete-framed structure, where about 80% of the load was as a result of self-weight.

The peer review indicated several areas of the critical transfer slab which were considerably under-reinforced. This could have led to structural failure of an element and a possible disproportionate collapse. Even in areas where reinforcement was within strength limits, there was concern that the designed structure lacked sufficient redundancy and was therefore not robust enough to withstand catastrophic disproportionate collapse. In such events, it is this 'redundancy' which will be relied upon to ensure the structure remains stable (even if only temporarily) to allow the safe evacuation of occupants.

The reporter understands that the issues were acknowledged by the original designer and amendments to the design were made.

In the opinion of the reporter, the issues stem from the inexperience of the designers in tackling such a structure, lack of competent internal checking and over-reliance on software. The lack of experience allowed the designers to proceed with the design not recognising the need to design the structure through all stages of its life, including those temporary conditions which would exist during construction. The reporter believes it is a case of 'rubbish in, rubbish out' as far as the modelling is concerned. Finally, checks should have been undertaken to ensure that software outputs mirror those which can be derived through conventional and empirical 'hand calculations'.

As part of the review, enquiries were made with leading bodies who are authorities on concrete construction and there seemed to be a lack of technical guidance on this subject. The current design codes (EC2, etc.) did not appear to cover the temporary modelling aspect in any significant detail aside from general statements to consider all stages of construction.

Additionally, the reporter is concerned that the published guidance is now around 15 years old and becoming increasingly outdated as more rigorous and detailed finite element-type analysis is undertaken. The reporter was also surprised to find that the IStructE's latest technical guidance on this subject, *Computational engineering*, does not even appear to consider the importance of this subject in modelling structures of this type.

In conclusion, the reporter considers that further technical guidance should be provided on the subject and perhaps even revisions to the aforementioned documents considered. Additionally, engineers should remain vigilant in undertaking simplified 'hand check' assessments and more should be done to reinforce this to more junior (and therefore inexperienced) engineers.

Key learning outcomes

For civil and structural design engineers:

- During design and checking consider the loads at each stage of construction
- It is good practice to carry out sense checks and validate all analysis and design outputs
- Ensure assumed construction methodology is communicated to contractors and is verified as constructible by the contractor, with any changes agreed with the designer
- Consider the need for robustness at all stages of construction
- Independent checking is good practice

Expert Panel comments

Unfortunately, it is not uncommon for lack of experience to lead to analysis models missing key construction stages, or those using the model failing to appreciate the presence of secondary load paths. In this case, the upper frames in the model were effectively acting as a Vierendeel truss. As suggested in the report, it is unlikely this was the intention, and very unlikely that the elements above had been, or could be, designed for the additional Vierendeel forces.

Other common mistakes include modelling one-way floor elements as a diaphragm such that the model assumes transverse bending in the floor, including torsional stiffness in elements but not checking the torsional resistance, column shortening reducing hogging moments for internal columns when the shortening is not present during construction and will depend on construction sequence.

While updated guidance, as suggested by the reporter, would be helpful, it can only ever give examples. It would not be a substitute for checking of the output by an experienced engineer who has an understanding of the expected behaviours. Here, the review engineer undertook a very simple load takedown and discovered that the much more complicated analysis was indeed incorrect.

It is essential that the temporary condition of the permanent works is considered at all times, as often the temporary condition of the permanent works can be more onerous than in the permanent condition. This must include giving full consideration by the designer of at least one buildable construction sequence. Early contractor involvement may be beneficial such that construction sequences can be modelled at the design stage. This will allow adequate consideration of temporary stages and their impact on the structure.

The Temporary Works forum provides significant guidance on constructability reviews. Had such a review been undertaken during design of this project, the errors would likely not have been made. Furthermore, the engineers involved would have benefited from a much broader appreciation of how design and construction are intertwined.

Structural robustness

The reporter is also right to highlight the robustness issues associated with transfer structures and particularly transfer slabs. The consequences of a failure in a transfer structure are potentially disproportionate and could lead to collapse. Guidance is provided in the IStructE document, *Practical guide to structural robustness and disproportionate collapse in buildings*, with further guidance for high-risk buildings. It is important to note that for transfer elements, simply providing normal building ties may not be adequate.

Assumed construction methodology

Under the Construction (Design and Management) Regulations 2015 (CDM 2015), it is normally the case that the structural designer should confirm in the pre-construction information how they have assumed the structural frame is to be built. Clearly, this information is essential in that the design is possibly only correct if the designer's assumed construction method and sequence are followed.

Where the contractor chooses a different construction methodology, then all parties should be aware that the design may no longer be correct. Indeed, the intended change in construction methodology may lead to the structure being unsafe or overly conservative. Where a change is proposed, the design must be re-assessed using the criteria appropriate to the new construction methodology. Failure to ensure that the design and proposed construction methodology are compatible may lead to a structure which is unsafe to build or indeed unsafe in use.

Designers may choose to state the assumed construction methodology as a condition of their design just as they would state the strength of steel and concrete.

The Health and Safety File should be updated after construction with whatever information is required to facilitate safe inspection, maintenance and eventual demolition of the structure.

Checking and validation

Computer-aided analysis and design is an essential part of much structural design, but it must be remembered that the software is only an aid to the designer. The design organisation must fully understand and validate all outputs. In this case, the supervising senior design engineer should have identified all shortcomings.

Safety demands that all computer outputs are subjected to a simplified sanity check, which appears not to have happened. The design firm's checking and validation protocols should have been appropriate to the complexity of the work in hand and considered the experience of the engineers involved.

Checking should be carried out at key stages in the design process before progressing to the next stage; consider checking 'basis of design', computer inputs/outputs, detailed calculations before checking drawings.

The importance of validating software is noted in *Proc. ICE – Civil Engineering*, August 2013: 'The importance of understanding computer analysis in civil engineering'.

Previous CROSS reports of interest include *Unconservative design of flat slab due to software modelling issues*.

It is to the credit of the checking engineer that the peer review considered the design more widely than simply assessing the information provided. This example highlights the value of independent third-party checks. The value of independent checks should not be underestimated since not only are errors found, but learning and development across teams are facilitated.

The full report, including links to guidance mentioned, is available on the CROSS website (report ID: 1073) at **www.cross-safety.org/uk/safety-information/cross-safety-report/concern-over-modelling-concrete-frame-building-1073**.

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