STRUCTURAL FIRE ENGINEERING ASSESSMENTS OF THE FRACOF AND MOKRSKO FIRE TESTS

Buro Happold

Anthony Abu - Florian Block - Neal Butterworth - Ian Burgess

Buro Happold Ltd - FEDRA and University of Sheffield

Introduction

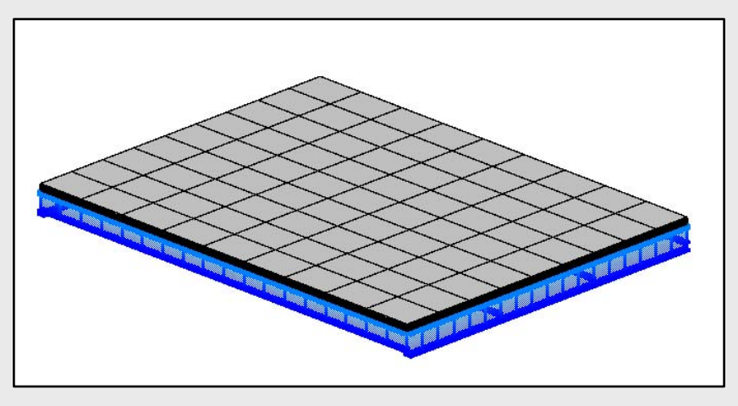
The fire engineering of steel and composite frame buildings has become more and more standard practice in the UK in recent years. Simplified design methods allow structural engineers to omit fire protection from large numbers of composite beams. However, there are always buildings which fall outside the relatively tight boundaries of the simplified methods, and more advanced analysis approaches, normally implying the use of general or specialist finite element programs, are used. Although, these programs have been extensively validated during their development against available test data, the way in which a model is created and its results interpreted is extremely important. This was seen during the "Round Robin" CFD modelling of the Dalmarnock fire test. Acknowledging that modelling of the dynamics of a fire is inherently less deterministic than that of the structural response of a building in fire, a similar lesson should be learned, as the effects of possible "modelling" mistakes could lead to catastrophic consequences.

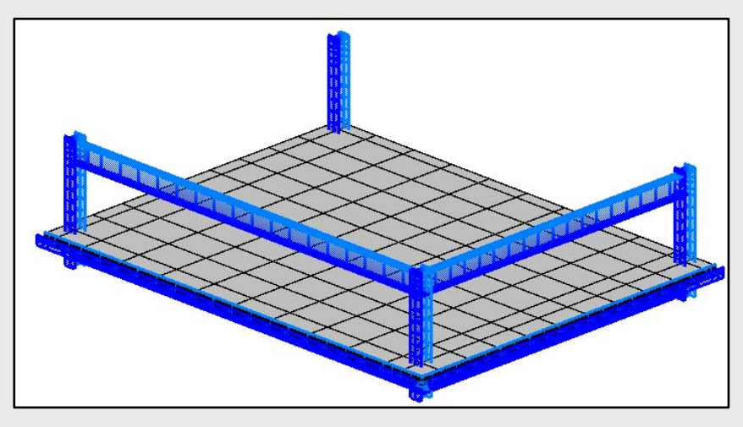
The FEM programs used to predict the structural response to fire have been validated against available test data. However, the bulk of the available test data comes from a series of just seven fire tests on a single building constructed in an old airship hanger in Bedfordshire, UK. The Cardington test building was designed as a typical composite frame building of the early 1990s, using standard UK building practice and details, which limits the available validation cases for the FEM programs to one particular type of construction. None of the tests led to the collapse of the building. The fact that the building techniques have developed further, and that finite element analyses of buildings in fire are conducted all over the world, means that programs are likely to be used outside the boundaries of the validations conducted. It is therefore even more important that parametric studies are carried out and that special care is given to the "modelling" assumptions and interpretation during the design process in order to give robust answers.

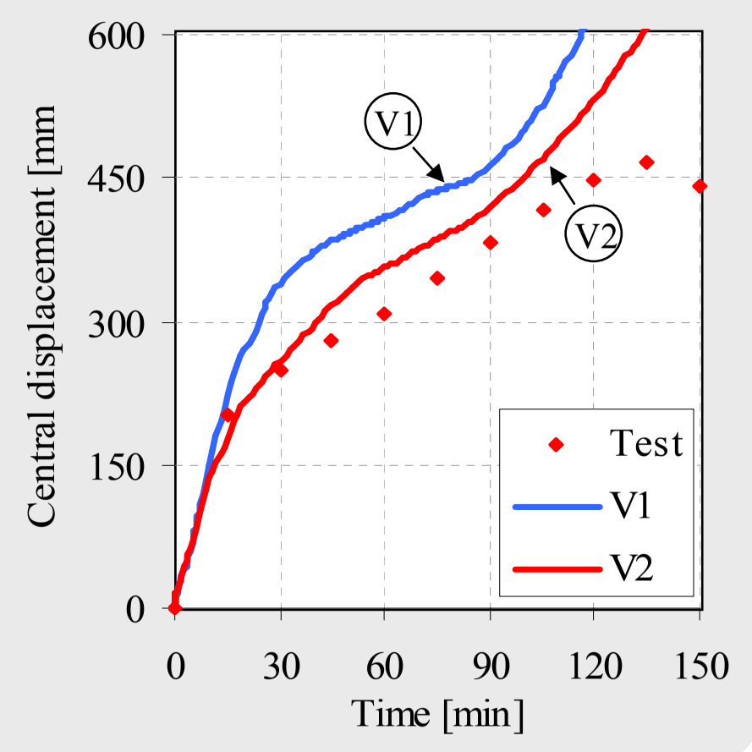
The FRACOF fire test

- The FRACOF test was designed to demonstrate the benefits of tensile membrane action in the design of steel-framed composite floor systems in the European Community.
- The test was set up as an 8.74m x 6.66m composite slab panel, representative of a corner compartment.
- It included four equally-spaced IPE 300 downstand secondary beams spanning 8.74m and as IPE 400 primary beams. The floor was supported by HEB 260 columns, using simple connections.
- The slab was 155mm deep, on COFRAPLUS 60 decking, acting compositely with the steel beams.
- Beams and columns at the edge of the structure were fire protected.
- Continuity across the two adjacent "internal" edges was simulated by welding the anti-crack mesh to the horizontally-aligned HEB 200.
- The slab was loaded with 3.9kN/m^2 as loading at the Fire Limit State.
- The underside of the structure was exposed to the ISO Fire for 120min.
- Integrity and insulation of the slab were lost after 105minutes, when a crack occurred due to weld fracture of the reinforcement but the stability was maintained for over 120minutes

Test predictions - FRACOF

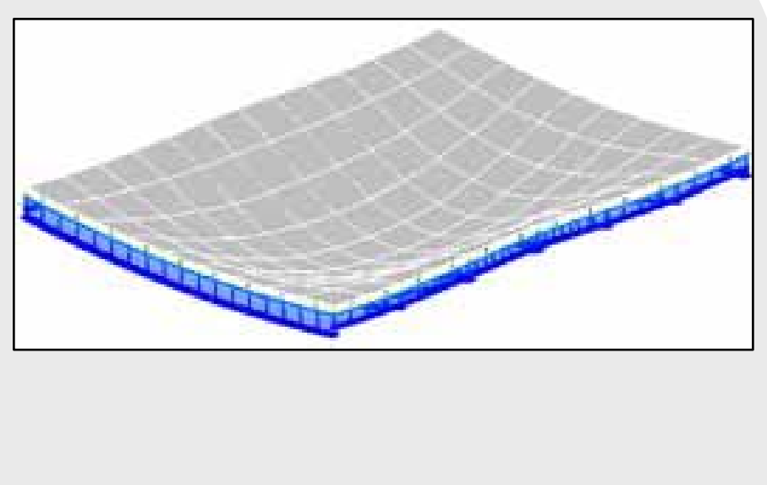






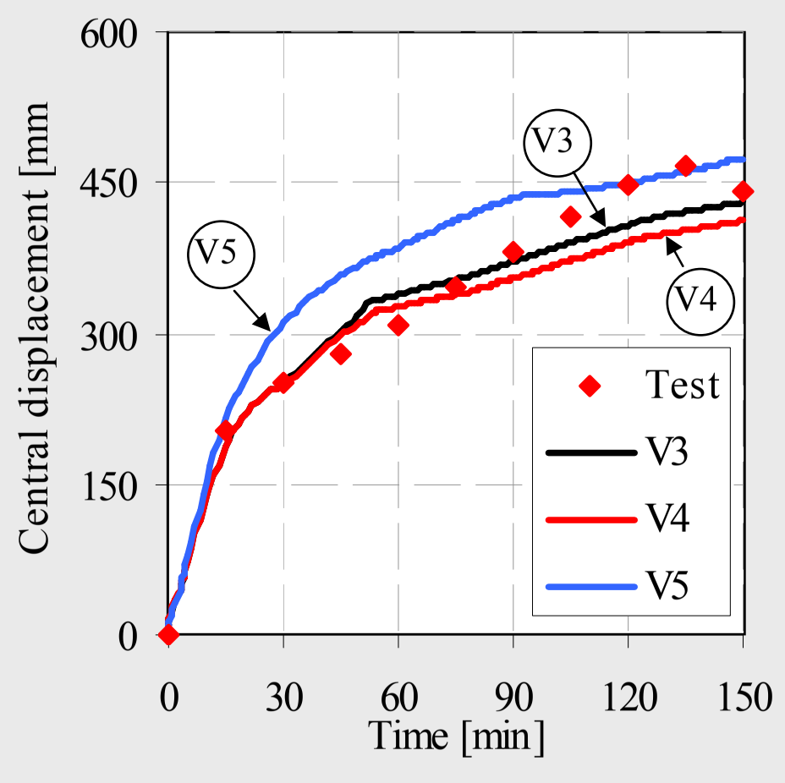
- Two models were analysed before the test using different modelling techniques.
- An overall slab thickness of 160mm had been specified in the brief, with no specific data on concrete strength but 40N/mm^2 used initially.
- The applied load was given as 3.75kN/m2, and it was assumed that slab continuity would be achieved along the two adjacent "internal" edges.
- The first predictions are based on protected beam and column temperatures following EC 3-1.2 calculations, making a conservative assumption of Cerablanket thermal conductivity. A One-dimensional heat transfer was used to predict the concrete slab temperature.
- The first *Vulcan* model (V1) considered an isolated slab panel, supported vertically at its corners, with protected beams providing the necessary vertical support along the slab edges. No axial restraints along its edges, but rotational restraints along two adjacent edges was assumed. The slab was modelled as 102mm thick continuous concrete layer above the decking troughs.
- The second *Vulcan* model (V2) used a full model of the test setup. It included the columns at the corners of the panel and the two horizontally-aligned HEB 200 sections along the "internal" adjacent edges for continuity. The orthotropic nature of the slab was accounted for by the using the *Vulcan* effective stiffness representation.

Test Assessment - FRACOF



- The initial predictions (V1, V2) conservatively estimated the test deflection, although exact structural detail was not available. The subsequent analyses however showed better predictions (V3, V4, V5) using more realistic protected beam temperatures, non-uniform temperature distributions and the average slab depth approach.
- It is noticeable that the *Vulcan's* estimate of deflection worsened as the integrity failure point was approached.
- The integrity failure in the FRACOF test was undoubtedly related to the lap-welding of the mesh, but it will be necessary in future to develop programmable criteria for this local slab fracture.

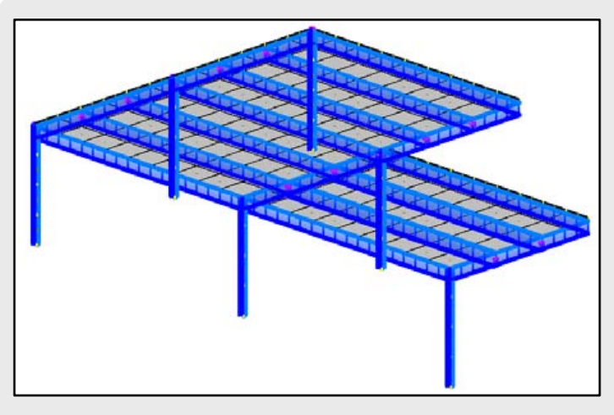
Parameter	V1	V2	V3	V4	V5
Concrete strength [N/mm^2]	40	40	37	37	37
Overall Slab thickness [mm]	160	160	155	155	155
Applied load [kN/m2]	3.75	3.75	3.87	3.87	3.87
Thermal conductivity [W/mK]	0.2	0.2	0.06	0.06	0.06
Protected beam temperature distribution	Uniform	Uniform	Uniform	Non-uniform	Non-uniform
Edge continuity condition	2 edges	2 edges	1 edge	1 edge	1 edge
Slab modelling approach	Thin continuous concrete	Effective stiffness	Effective stiffness	Effective stiffness	Average slab depth

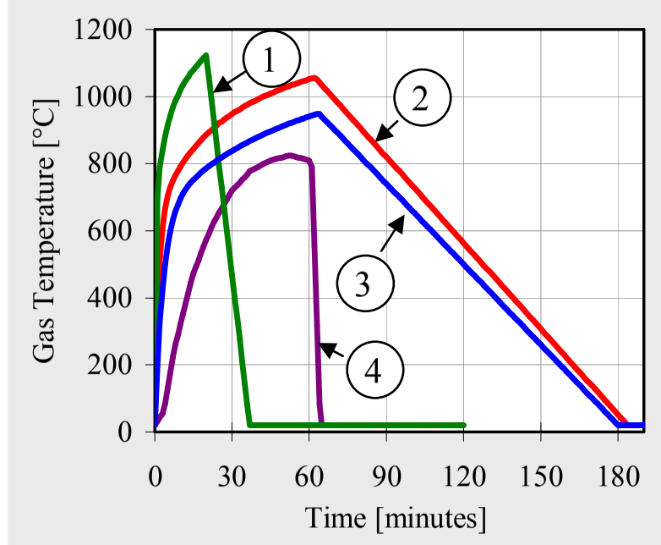


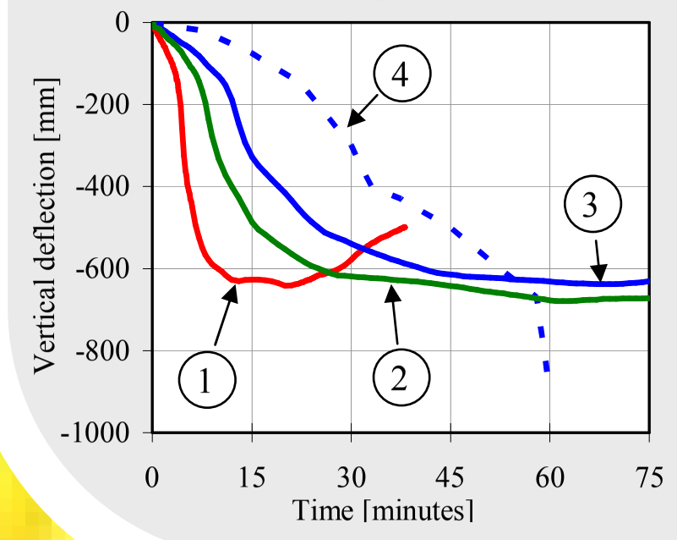
The Mokrsko fire test

- 18 September 2008 at Mokrsko by the Czech Technical University of Prague.
- Represented one floor of a steel and concrete composite office building consisting of four bays with a size of 9m x 6m each.
- Tested three different floor systems:
  - "Angelina" composite beams developed by Arcelor-Mittal with elongated web openings,
  - Beams with corrugated webs made from thin steel plates, and
  - Precast hollow-core panels.
- 120mm composite slab CF46 metal decking using a smooth mesh (196mm^2/m) and 12mm bars in each rib.
- The connections of the Angelina beams were specially designed endplates which only connected the top flange and a small part of the web of each beam.
- The bases of the columns were constructed as pinned.
- The imposed load of 3.0kN/m2 on the slab was generated by sand bags, and the self-weight of the floor system was 2.6kN/m2.
- Timber cribs generated a total fire load of about 620MJ/m^2
- Steelwork fire protection was omitted from all Angelina beams, as well as the beams with corrugated webs. The rest of the steelwork was fire-protected.
- This protection arrangement generated a 9m x 12m bay of unprotected Angelina beams, and a 9m x 6m bay of beams with corrugated webs, surrounded by protected beams.
- After about 61 minutes three quarters of the structure collapsed.

Test Predictions - Mokrsko

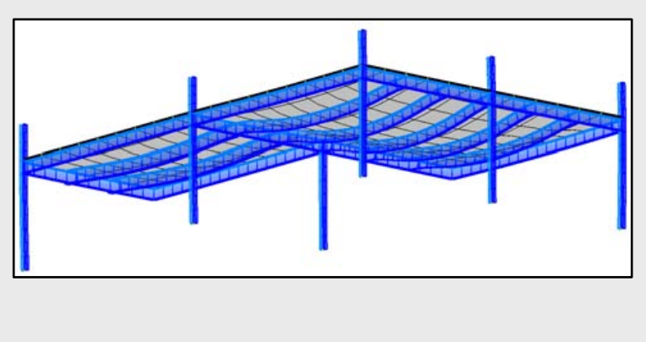


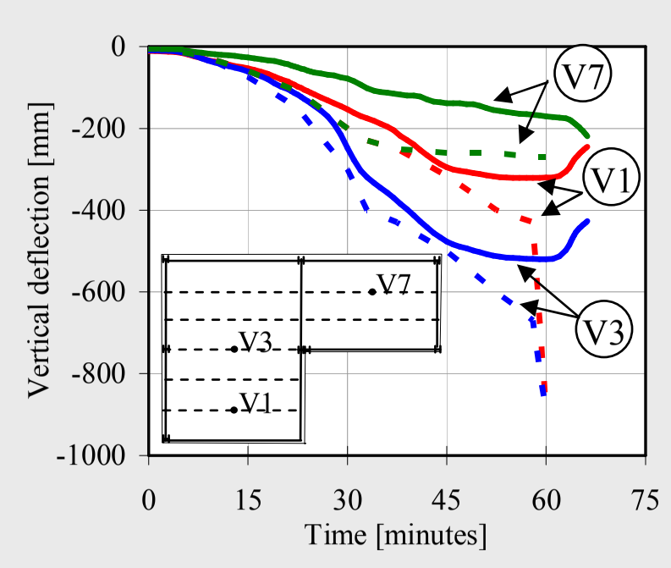


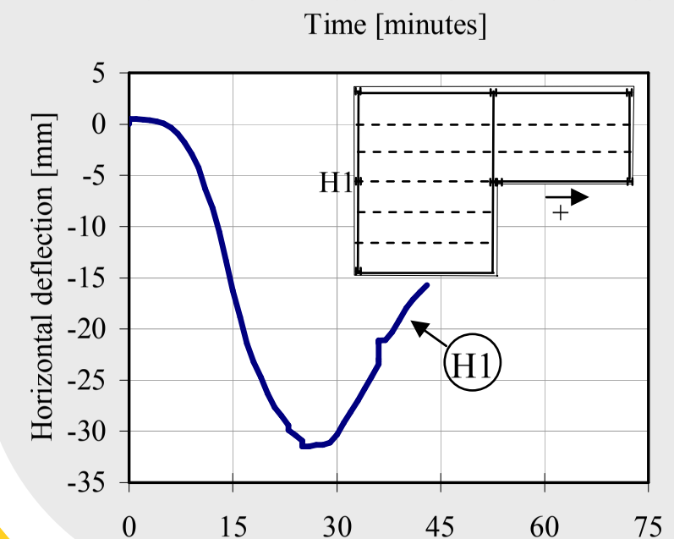


- Before the test, it was modelled using *Vulcan* based on the available data.
- Only the 3 bays with the composite slab were modelled, and the Angelina beams and the corrugated-web beams were represented using an effective web thickness approach.
- As with a normal SFE project a number of parameters were varied in order to test the robustness of the solution. The fire was altered to produce a short-hot fire (1) and a cooler-longer fire (3). The beam connections were initially modelled as rigid, which tends to be acceptable for normal composite connections designed to UK design rules in braced frames.
- The real fire (4) burned significantly cooler than the predicted fire (2). shows the resulting vertical deflections from the test and the three different design fires at the middle of the large bay (9m x 12m) of Angelina beams.
- The predictions show a much earlier increase in deflections than the experimental results. This is because the parametric fire curves represent post-flashover fires, and should be moved by about 15min to give a realistic representation of the fire. This greatly improves the comparison.
- The models continued beyond the failure point of the test at about 61minutes, and do not show any indication of collapse, however the vertical deflections larger than span/15, which would normally result in an increase of reinforcement to limit the vertical deflections. Furthermore, all beams framing into columns would be protected in a robust design for fire.

Test Assessment - Mokrsko







- After the test results were released, the actual temperature data was used as more accurate input data to the *Vulcan* model.
- The deflection curves show that when the real temperature data is used the vertical deflections are represented accurately up to about 44 minutes.
- The small vertical differences are due to the edge beam deflections, which are lower than those seen in the test, as well as to the use of average compartment gas temperatures to heat all elements.
- The difference between prediction and reality for the beams with corrugated webs (V7) can be explained by the observed shear buckling of the thin webs, which cannot be represented by the chosen way of modelling the beams.
- Due to the very flexible beam connections, another set of analyses were conducted in which the connections were modelled as pinned.
- In these cases the *Vulcan* models predict failure at around 43 minutes using the experimental fire temperature data. It can be seen that this is the point at which the *Vulcan* and test results diverge.
- The figure on the left show the horizontal displacement at the top of the edge column connected to an unprotected Angelina beam. It can be seen that, after an initial outwards movement due to thermal expansion of the structure, the column moves inwards due to pull-in by the vertically-deflecting Angelina beams.

Conclusion

In this study, it is again confirmed that it is possible to make conservative overall predictions of the response of composite structures to fire using sophisticated finite element programs and that modelling can be accurate with accurate data. However, in both test cases it was not possible to predict the exact failure mode or time prior to the tests. With the accurate data given by the tests a fairly accurate representation of the structural behaviour can be made, and this implies that conservative assumptions will produce conservative predictions. However, everybody who predicts the behaviour of structures in fire using finite element analysis should validate their modelling against simple and well documented experimental data.

- *Vulcan* could model the overall behaviour of both fire tests accurately when the correct input data was used
- The tests showed again that failure is often caused by details and therefore robust construction details should be used until computer modelling can include these phenomena
- The predictions of the Mokrsko fire test showed that the test set-up would have not be sufficient for a real building.
- If finite element analyses are used to justify the behaviour of non-standard forms of construction, which are most likely to lie outside the bounds of software validation, great care should be taken when modelling these problems, using detailed parametric studies and possibly even physical fire testing.

Florian.Block@Burohappold.com

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Ian.Burgess@Sheffield.ac.uk