Substitute load optimisation in full-scale laboratory tests of orthotropic plates

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Abstract

It is common in full-scale laboratory tests to simulate live or transient loads of secondary importance with generic weights, even if the load being simulated is uniform in nature. For many simple structures, such as beams or plates, calculation of appropriate substitute load is rather straightforward. The paper deals with somewhat more difficult case of orthotropic plates, which are common solutions for fire resistant roofs. The main load of these structures in tests according to EN 1363 [2] is temperature, but uniform load must also be included in the tests. A numerical algorithm is proposed to beforehand calculate an applicative load which preferably would not impair neither favour the test specimen. An FEA model of the roof specimen is built and optimisation algorithm seeks for the solution, taking into consideration all of the arbitrarily formulated constraints for the load distribution and a set of independent objective functions. In the paper, few such objective functions, appropriate in this kind of tests, are discussed.

Keywords: full-scale laboratory tests, load, optimisation, fire safety, roofs, orthotropic plates

1. Introduction

The fire resistance of roof structures with trapezoidal steel sheets is determined by full-scale fire resistance laboratory tests. Equipment and conditions for test method of roofs are given in the standard EN 1363 [2] (part 1 and 2). Roofs are tested for the fire applied from below and in most cases with heating conditions according to the standard temperature–time curve. Loads taken into consideration in the structure design process are also considered, mainly: snow load or other permanent and variable actions imposed on the roof, and loads from structures suspended under the roof, e.g. ventilation systems.

Resolution of a substitute load is relatively easy in a case of a structure consisting of independently deflecting beams. In such case, each of these beams can be loaded irrespectively of others. The case of rectangular, isotropic plate is somewhat more difficult, but it is still possible to calculate universal load schemes, dependent on plate edges length ratio, etc. The case is different for orthotropic plates, such as trapezoidal sheet roofing, which stiffness in one perpendicular direction is distinctly greater than in other direction. In this case, each repeated trapezium will behave alike a single beam, therefore they should be loaded independently, although significant mechanical constraint also exists between these “virtual” beams. This constraint will be different in each case, what prohibits one from using simple solutions of beam or plate structures.

Moreover, in laboratory test the specimen is supported on two edges and has a finite width in the direction perpendicular to the span; but the test should mirror a theoretical situation of “infinitely wide” plate, that is a plate which trapeziums repeat limitlessly in the direction perpendicular to the span. The case of the unlimited plate will be thereafter called “prototype scheme”, and a case of finite width plate with edges perpendicular to the span unsupported − “laboratory scheme”. Even ideally uniform loading in laboratory scheme would not result in structural response adequate to prototype scheme. In the instant of loadbearing capacity depletion, edge zone will be more eager to be excluded from structural integrity, what will cause chain increase of yield in the centre of the plate and earlier local buckling. The case becomes even more problematic when the load is simulated by pointwise suspended weights.

2. Methodology

A system for optimal resolution of the load was developed. The system calculates locations of weights by comparison of orthotropic plate response under uniform loading and under concentrated forces. The plate is modelled with 12 DoF shell elements of FEA. Proprietary solver was developed in Python 2.7 language, based on LAPACK library and optimisation technique based on modified algorithm of simulated annealing [1] (similarity of the name with fire engineering topic is coincidental.) The load placement is considered as a phase space of the problem. Since the algorithm may search for optimal resolution for arbitrarily chosen loading and support conditions, it is even possible to counter the above-mentioned problem of laboratory scheme, by such load distribution, that the edge zones will be deflected similarly to the centre of the plate, and their premature failure will not occur. Simulated annealing algorithm is always convergent, but may also produce suboptimal results, therefore some fine-tuning and statistical processing of repeated simulations is also needed.

3. Example results

As an example, a simplistic optimisation of the load for a 4000 mm × 3395 mm roof is presented. The cross-section of the roof is trapezoidal steel sheet with a thickness of 0.75 mm,

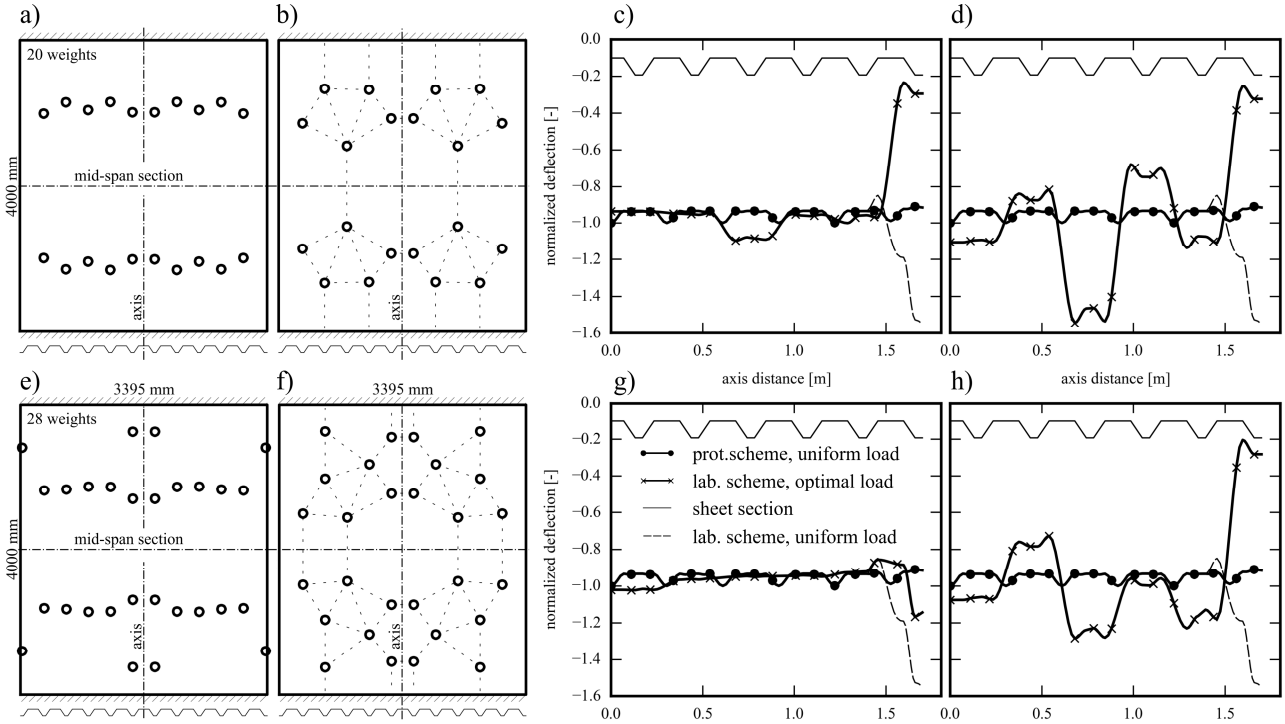

Figure 1: Optimisation with deflection (a,c,e,g) and deflection and distribution (b,d,f,h) criteria. Weights placement (a,b,e,f) and deflection in mid-span section (c,d,g,h). ("prototype scheme" and "laboratory scheme" explained in the text.).

module of 305 mm, the height of 92 mm, the width of the top and bottom flange of 140 mm and 40 mm respectively. For simplicity and generalisation of considerations in this paper, details of the structure such as small extrusions, grooves, joints, support details, etc. were neglected. For the sake of symmetry of the structure in both perpendicular directions, only 1/4 of the structure was analysed. The model had 11808 DoFs. The first major constraint is a restriction of the load placement only to axes of bottom flanges. This constraint is required for practical purposes in laboratory testing. As an initial objective function of the optimisation process, the conformance (in the sense of least squares) of the deflection in the mid-span line in laboratory scheme with a deflection in prototype scheme under uniform load was chosen. In real applications, multiobjective optimisation [4] adapted to specifics of the structure is performed. It is also possible to use non-linear conditions in objective function or change of stiffness of the material caused by the rise of temperature. In the example, the deflection was normalised to the dimensionless value of 1.0 for the maximal, vertical deflection in prototype scheme. Optimal placement of concentrated load was calculated with 20 or 28 weights. Results of deflection in the mid-span line are shown in Figure 1.

Inspection of the load distribution (Figure 1a,e) shows that weights should be placed approximately in two parallel lines in 1/4 and 3/4 of the span. Moreover, four weights in Fig. 1e are localised in the outermost bottom flange, which is an incomplete part of the specimen, hence troublesome in practice. This situation is caused by overly simplistic objective function. Other aspects of structure response, such as stress, buckling, etc. should be considered. Since these structure parameters are qualitatively similar in applying in the optimisation procedure, another one is presented. The load distribution should be not only theoretically correct but also practically applicable. This requirement depends on many technical details characteristic to the laboratory. In this paper, it is presented as a requirement of appropriate distance from each concentrated force to their neighbours.

The requirement of weights spatial distribution is achieved by calculating a Gabriel graph [3] for each distribution and calculating the secondary fitness based on standard deviation of distances between neighbours and supported edges of the roof (free edges were excluded on purpose). Both objective functions (for deflection and load distribution) are further combined by means of multiobjective optimisation techniques. As one may expect, this leads to decrease in quality of optimal solution for deflection fitness (Fig. 1d,h), but yields much more practical distributions of concentrated loads on the specimen (Fig. 1b,f). In both cases (Fig. 1d,h) the edge of the specimen is under-deflected, because of lack of a weight in the outermost bottom flange.

Even on a modern desktop PC calculations are fast enough to be considered real-time. This renders presented system a useful tool in daily practice for a trained operator, who may test various conditions and constraints for specimen loading, accordingly to the laboratory conditions and their experience, supporting engineering judgement with objective calculations.

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