ARTICLE IN PRESS

Fire Safety Journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Optimising design decision-making for steel structures in fire using a hybrid analysis technique

Obinna Akaa*, Anthony Abu, Michael Spearpoint, Sonia Giovinazzi

Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch 8140, New Zealand

ARTICLE INFO

Keywords:
Structural design
Structures in fire
Protection of steel
Fire design stakeholders, Design uncertainties,
Optimum decision-making

ABSTRACT

Steel structures can be protected against the effects of fully-developed fires by the use of sprayed on materials, board systems and intumescent paints, etc. or by using sufficiently large unprotected elements. This paper presents how optimum decisions for the protection of steel structures in fires can be achieved in a performance-based design environment, given conflicting structural fire design decision criteria and multidisciplinary fire design stakeholder views. In particular, a novel hybrid analysis approach is proposed for combining stakeholder views on the different fire protection options and the numerical outcomes of structural fire analysis. As for the stakeholder views, reference is made to benefits and costs criteria priorities for assessing competing options resulting from a previous study from the same authors. The fire protection structural performance is numerically and probabilistically assessed according to a parametric study. The proposed approach is exemplified by making reference to a limit state structural fire design of single steel elements. A synthesis and ranking technique is then applied to integrate the qualitative results obtained in terms of benefits and costs priority scores; and the quantitative measures of failure probabilities and costs for the different fire protection options. The results show that the ranking technique accounts for multidimensionality in synthesising the structural fire design decision problem. The results also show that intumescent paints and board systems are the most cost-effective options in different stakeholder influence scenarios, given a general selection of steel structural fire protection. The hybrid technique is proposed to support an optimal and cost-effective structural fire design decision-making for buildings in a performance-based design environment.

1. Introduction

Fire phenomenon is highly dynamic. To achieve fire safety in terms of life, property or environmental safety, there must be deliberate consideration and optimisation of fire safety design decisions. Decisions made at different stages of a structural fire design process are affected by uncertainties. This is due to the impossibility of gaining complete and accurate analytic or design information needed for the structural fire design especially in the initial design stage when a number of decisions have to be made. The presence of uncertainties is acknowledged in various design standards by the use of safety factors for many design conditions. Structural fire design entails guaranteeing that there should be an acceptably low probability of failure of the building structure [1]. In the design of structures in fire conditions, the uncertainties can range from variable parameters to structural fire models, human error and decision re-evaluations [2].

In the design of steel structures for fully developed fires, the use of different fire protection options such as board and sprayed on systems, intumescent paints etc., with performance-based codes and varying interests of multiple stakeholders may lead to design uncertainties in achieving steel structural fire design adequacy. There is the need to develop a quality decision analysis procedure which is able to extract and manage varying stakeholder views, integrate structural fire analysis outcomes and rank the competing design options for optimum decision-making. This will help balance fire design stakeholder desires and reduce design uncertainties in achieving rational design solutions to meet performance objectives.

This paper demonstrates the applicability of a hybrid decision-making technique, referred to here as GAT, consisting of the joint implementation of three approaches, namely: the geometric mean method (**G**MM), coupled with the analytic hierarchy process (**A**HP), and the technique for order of preference by similarity to ideal solution (**T**OPSIS). The use of the hybrid decision-making GAT technique is proposed in this paper for the effective integration of fire design stakeholder priorities, failure probabilities and costs of steel structural fire protection towards optimal design decision-making. Firstly, the

---

* Corresponding author.
E-mail address: obinna.akaa@pg.canterbury.ac.nz (O. Akaa).

http://dx.doi.org/10.1016/j.firesaf.2017.03.018
Received 14 February 2017; Accepted 15 March 2017

Please cite this article as: Akaa, O., Fire Safety Journal (2017), http://dx.doi.org/10.1016/j.firesaf.2017.03.018

decision-making process in steel structural fire design is discussed. The GAT process is then described; the use of GMM+AHP for the selection of applied fire protection to steel structures has been a precursor to this paper [3]. The formulated benefits and costs decision criteria used in assessing competing fire protection options, as well as the stakeholder engagement and paired judgement process on the decision criteria achieved in Akaa et al. [3] are considered here. The steel structural fire design criteria and options are formulated based on single-element design; structural system design is not being investigated for simplicity, and to highlight the benefits of the proposed technique. Here, the priority scores of qualitative benefits and costs design decision criteria from aggregated paired judgements of 46 fire design stakeholders are used. This is an expanded sample set compared to the 30 stakeholder views analysed in Akaa et al. [3]. The fire protection options used in the investigation are board systems (*BST*), sprayed on cement-based materials (*SCM*), intumescent coatings or paints (*ITC*), concrete encasement of steel (*CES*) and the use of unprotected steel (*UPS*). The competing fire protection options are critically assessed through deterministic and probabilistic analysis of structural steel in fire. The outcomes from the analysis are integrated into the decision analysis using TOPSIS. The result accounts for the multidimensionality in synthesising qualitative expert opinion and quantitative parametric study as well as optimising the structural fire protection decision-making.

2. Decision-making in steel structural fire design

Given conflicting factors (e.g. safety, environmental, socio-economic, among others), human beings usually make judgments based on their knowledge, experience or outcomes of costs-benefits/risk analysis [4]. These bases of human judgements are also instrumental in deciding among solutions to a problem that has multiple attributes such as the decision goals, diverse criteria etc., whereby a decision-maker is required to compare these attributes to assess the suitability of the various decision options. Nevertheless, some conflictual multiple attributes or criteria in decision-making processes may resist simple solutions and would need some optimisation. A typical instance is in the conceptual and formulated design of buildings for fires, which involve multidisciplinary stakeholders; namely: *building owners, fire and structural engineers, architects, fire service personnel, building consent authorities, building contractors, environmental professionals, manufacturers and suppliers, building insurers, building services and end-users*. These fire design stakeholders have varying opinions on the appropriate design option within conflicting design decision criteria of safety, economy, societal and environmental considerations. Hence, given the flexibility of using engineered solutions in meeting performance objectives and the existence of multiple design solutions, there is a potential of design decision uncertainties in achieving optimum designs.

In the design of steel buildings for fully developed fires, structural fire protection needs appropriate discussions and consensus among design stakeholders as well as critical assessments to mitigate uncertainties for suitable or optimum design decision-making. For instance, from a building owners' perspective insufficient funds can be a major constraint prompting them to select sprayed on materials, which are adjudged as an economical passive fire protection for steel structures in fire [5]. Architects in this context may advise against sprayed on systems due to their poor aesthetic appeal and rather support the use of intumescent paints, which express the visual appeal of the building. However, building contractors may be against sprayed on systems and paints due to the wet application on site which may impede the activities of other trades. Hence, contractors may prefer the use of board protection, which may not be easily accepted by the building owner given their budget constraints. Fire and structural engineers in this case may support an optimisation of the entire design to exclude the use of passive fire protection and leaving the steel structures unprotected. This may be challenging for the building owner who may also be keen on ensuring a functional building for end-user comfort as well as the building insurer whose financial risk tolerance is challenged to insure a building having unprotected structural members against fires. It is noteworthy that there are other divergent views on appropriate fire protection of steel structures from the perspective of other stakeholders not mentioned here; a full discussion on possible views of fire design stakeholders is out of the scope of the paper and can be found elsewhere [3].

In addition to the divergent stakeholder views, interests or preferences, there are also unavoidable design uncertainties given the variable analytic parameters (including basic variables e.g. unit weights, steel density, yield strength etc.) considered in fully implementing a performance-based steel structural fire design. This is also significant as the behaviour of material properties of steel at elevated temperature may be uncertain during structural stability assessment e.g. variation of yield strength of steel at elevated temperature. These uncertain parameters in structural fire design and varying interests of fire design stakeholders culminate in decision-making and inform the need for a robust design decision analysis technique or procedure that allows the integration of these uncertain variables for optimised design decisions.

3. Methodology

As introduced previously, to completely address the structural fire design decision-problem in this paper, the use of GAT, a hybrid MCDA technique, which integrates GMM+AHP+TOPSIS, is proposed. Hybrid MCDA techniques have been developed and applied conveniently to very specific complex decision problems. In a construction project bidding process, Liu and Yan [6] applied a combination of AHP+Multi-criteria Optimisation and Compromise Solution (VIKOR) to select the best contractor out of four, assessed under five decision attributes. AHP was used in the prioritisation of decision attributes, while VIKOR was used to carry out the final synthesis and ranking of the competing contractors. More applications of hybrid MCDA techniques to specific decision-making problems are discussed elsewhere [7]. The choice of GAT in this context is due to its capability to aggregate multiple expert or stakeholder judgements into a single group judgement through GMM. It seamlessly weights or prioritises the group judgements on the conflicting decision criteria through AHP and synthesises qualitative/quantitative criteria weights to assess and rank the competing options through TOPSIS. TOPSIS [8] was developed on the basis that the best decision option is the one having the closest geometric distance to the ideal solution. TOPSIS considers the following decision criteria: qualitative criteria, quantitative benefit and cost criteria. In its application two artificial options are hypothesised: (a) the ideal solution (i.e. the one which has the best level for all criteria considered); and (b) the negative ideal solution (i.e. the one which has the worst criteria values). At the end of the analysis, TOPSIS selects the option closest to the ideal solution and farthest to the negative ideal solution. The main assumptions in applying TOPSIS are that all decision criteria should be independent and the value of each decision criterion should be one-dimensional. TOPSIS has been applied in many complex decision-making problems including supply chain, energy, engineering and human resources management etc. [9]. Notably, AHP has been combined with TOPSIS to comparatively select a cost-effective seismic retrofitting option with reference to a case study, which involved assessing other single and hybrid MCDA techniques [10]. In a tunnel study, Golestanifar et al. [11] applied AHP+TOPSIS to rank three tunnel excavation options based on seven conflictual decision criteria within methods of rock excavation and characterisation. In these studies, AHP was applied to prioritise the established decision attributes, which were synthesised and ranked through TOPSIS. The strengths of AHP+TOPSIS in analysing larger decision attributes, by integrating quantitative and other analytical priority scores in a MCDA,