Application of Expert Judgment to the Quantification of a Damage Scale for Reinforced Concrete Buildings Exposed to Fire

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ABSTRACT: Essential in the fire fragility assessment of mid-rise reinforced concrete buildings is a relevant damage scale. This study adopts expert elicitation to construct a damage scale relevant to the slabs of these buildings by relating thresholds of four structural response measures (i.e., spalling, residual capacity, peak rebar temperature and deflection) to three qualitatively described damage states of increasing severity. The opinions of thirteen international experts are pooled together using Cooke's Classical Model, which recognizes that uncertainty exists around each damage state threshold and seeks to quantify it. Compared to an approach which weights exert opinions equally, this Model results, in most cases, in conservative estimates of the damage state thresholds associated with well-constrained uncertainty. Areas where more research is needed are also identified. These areas include the determination of the thresholds of the first three measures when the extensively damaged slab cannot be repaired, and of the residual capacity of any of the three considered damage states.

1. INTRODUCTION

Fires can cause substantial structural damage to buildings, as evidenced by multiple fire-induced structural failures of buildings in recent decades. Nonetheless, to date reliable methods to accurately predict the economic losses suffered by a building in a future fire have not been developed. There has been a recent trend towards the development of a probabilistic framework for structural fire-loss estimation, in line with the PEER framework being applied in earthquake engineering, e.g., Lange et al. (2014). However,

an essential component of this framework is knowledge of the building's fragility, which represents the likelihood of damage suffered by a given building, in a range of possible future fires.

To date, research in this area has focused almost exclusively on steel-framed, steel-concrete composite buildings (e.g. Lange et al., 2014), and no research appears to have been performed to quantify the fire fragility of cast-in-place reinforced concrete (RC) structures (Bisby, 2013). As a first step in this direction, the current paper considers the response to fire of a mid-rise cast-in-place concrete frame, in an attempt to

define damage scales for this important class of buildings.

A key component in fragility assessment is the construction of a damage scale relevant to the examined building class. This scale consists of a number of discrete damage states, which ideally include all the possible types of damage that a building of the given class might sustain when exposed to fire. An ideal damage scale should (a) provide a clear and unambiguous description of the expected observed damage in each state, (b) be able to relate the simulated structural performance of a building in fire with each state, and (c) relate each state with a level of repair and an associated repair cost; such damage scales have not yet been produced within the structural fire safety engineering community.

This study focuses on the construction of structural response-to-damage relationships, relevant for the slabs of RC open plan buildings, which meet the first two requirements ((a) and (b)). Due to poor quality or unavailable real fire and experimental data, these relationships are constructed herein by combining the responses of thirteen international structural fire engineering experts who participated in an expert elicitation workshop at the 7th International Conference on Structures on Fire (Shanghai, China). This was organized as part of a joint research project by University College London and the University of Edinburgh. Rational consensus on the judgments of the group is reached by pooling their responses using Cooke's Method (Cooke, 1991).

2. FRAMEWORK

The focus here is on relating structural response measures to discrete damage state descriptions for the fire fragility assessment of critical structural elements of RC office buildings. The main components of this damage scale are briefly discussed.

2.1. Building class

The specific building selected for the initial study is based on a concrete structure tested during the Cardington Concrete Frame tests in the UK (Bailey, 2002). This specific building is selected as it represents a typical modern, mid-rise concrete cast in place frame, of scale and dimensions that might be expected for an open plan building in the UK. This will also allow for future comparison against a steel-framed composite building also tested under fire at Cardington (British Steel 1999). Nonetheless, it should be noted that the global response of a building exposed to fire is not well understood. For this reason, this study is concentrated on the RC slabs of the selected building class, as they consist the most critical structural elements.

2.2. Damage scale

The Concrete Society (2008) has produced a damage scale for visually assessing the damage of four RC structural elements (i.e., slab, column, beam and wall) exposed to fire. The scale also suggests repairs for each damage state description. This scale is used herein to classify the damage sustained by individual structural elements based on observations of the surface appearance of the concrete. In particular, the scale adopts indicators such as the condition of plaster, the color of the surface and the level of crazing, and its structural condition, as well as qualitative descriptions of spalling, cracking and deflection or distortion. The scale consists of five states of increasing severity ranging from none to extensive damage, and each state is associated with a level of repair, as depicted in Fig. 1. Nonetheless, this damage scale falls short of the needs of fragility assessment since it does not relate the damage states to quantifiable measures of structural response. This paper attempts to fill this gap by building structural response-to-damage relationships.

2.3. Structural response measures

Appropriate structural response measures for the assessment of fragility are those that increase with an increase in fire intensity. In the current study, four structural response measures have been selected, namely: (1) amount of concrete spalling, (2) vertical deflection of the floor-plate, (3) peak rebar temperature, and (4) residual stru-

DS	Surface Appearance of concrete			Description
	Condition of plaster/ finish	Colour*	Crazing	
ds_0	Unaffected or beyond extent of fire			
ds_1	Some peeling	Normal	Slight	Damage primarily cosmetic in nature, which does not impact on the design or repair of the structural fabric of concrete building.
ds_2	Substantial loss	Pink/Red	Moderate	A small amount of damage has been experienced by the element to the effect that some small scale remedial action is required to enhance the element's remaining ability to perform its structural function(s).
ds_3	total loss	Pink/Red Whitish grey	extensive	The element has experienced a significant, but not catastrophic, amount of damage to the effect that, with significant remedial action, it can be reinstated to perform its structural functions
ds_4	destroyed	whitish grey	surface lost	The damage caused by the fire is so extensive that it is no longer viable to repair and reuse the element and replacing the element with a new element is the only option. The building has not suffered a disproportionate collapse.

Figure 1: Characteristics of the damage scale, adopted in this study, based on the scale proposed by the Concrete Society (2008).

ctural capacity (i.e. the proportion of nominal ambient temperature load capacity retained). Measure (1) is chosen because spalling is widely regarded as a critical parameter in assessing fire damage to concrete buildings (Concrete Society 2008); parameters (2-4) are selected because they are often used as end-point criteria in standard structural fire tests on isolated structural elements, and because they can be quantifiably assessed by testing or analysis.

2.4. Uncertainty in structural response-to-damage relationships

In the current study, structural response-to-damage relationships provide structural response measure thresholds that correspond to each damage state. The main interest here is on the expected (mean) value of this threshold for a given damage state, as well as the quantification of the uncertainty around its value. These are determined by estimating the parameters of a probability distribution function according to the properties of each structural response measure.

In particular, for structural response measures whose values range between (0,1), their threshold at a given damage state is assumed to follow a beta distribution.

Similarly, for strictly positive structural response measures, their threshold at a given damage state is considered to follow a lognormal distribution.

3. EXPERT ELICITATION METHODOLOGY

The key is to determine how a damage state sustained by RC slabs can be related to thresholds of four response measures. In similar fields, for instance in earthquake engineering, these thresholds are often determined empirically from tests. Given the novelty and poor understanding of the fire problem combined with the lack of relevant experimental data, an expert elicitation is undertaken; this recognizes that uncertainty exists around each level, and seeks to quantify it.

The main challenge in any expert elicitation is in rationally combining (i.e. weighting) the experts' differing opinions; some experts are better at judging the uncertainty around a random variable than others. This challenge is addressed herein by adopting Cooke's Classical Model (1991), which ranks a group of experts according to their ability to judge uncertainty distributions

for a number, *n*, of seed random variables (Fig. 2). From the experts' responses, a performance-based weighting for each expert is defined by combining objective metrics: (1) calibration, i.e. statistical accuracy, score and (2) information score, which represents the degree to which the sample distribution proposed by the expert is concentrated compared to a reference uniform distribution.

3.1. Combining experts opinions

The weight assigned to each expert is the product of their *calibration* score with their *information* score. These weights are then used to combine the experts' opinions on target items using linear pooling. Expert weights can be either global or item weights; the former are obtained jointly from the seed questions and are applied uniformly to all target questions. By contrast, item weights are calculated for each target question per expert based on a combination of their calibration score from the seed items and their informativeness on the particular target question.
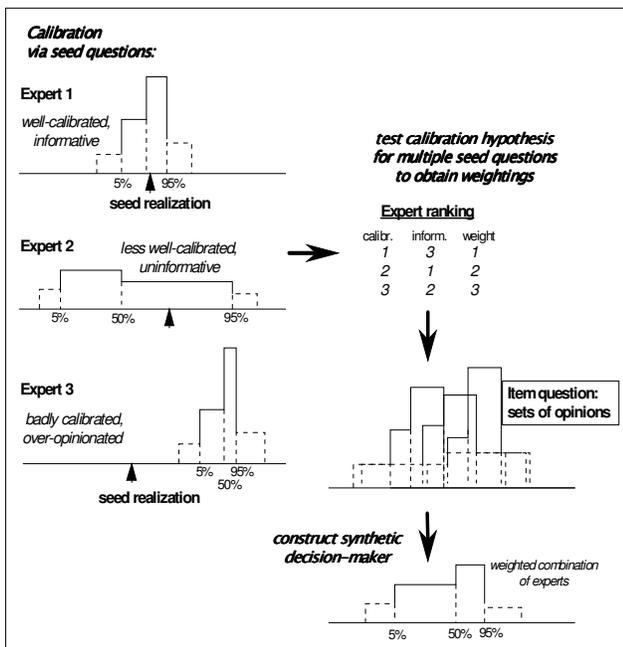

Figure 2: Ranking of experts based on the information and calibration score.

4. CASE STUDY

The Classical Model expert elicitation method is used herein to elicit and construct a structural fire damage scale relevant for elements of RC office buildings. The particular descriptive qualitative discrete damage states of the adopted scale relevant to RC slabs are related to thresholds of four structural response measures by combining expert judgments. The uncertainty in the exact value of each threshold is also taken into account.

In what follows, a brief description of the experts' background is provided, the structure of the workshop and a brief description of the selected building class, the damage scale and the structural response measures adopted is provided, along with a discussion of the main results and outcomes.

4.1. Background of Experts

Information regarding the background of the thirteen experts, all of whom agreed to participate in the expert elicitation workshop, was gathered using a pre-workshop survey. The experts' responses showed that they had experience in 217 RC buildings of different heights, structural systems and ages. Their experience was mostly research-based. The experts had participated in the construction or design of only 23% of these 217 RC buildings. All experts had experience of experimental or analytical methods of investigating the performance of RC elements in fire, but only 25% had ever assessed (or even visited) a real fire-damaged RC building. Finally, all experts were novices in formalized expert elicitation.

4.2. Building class

The building class examined herein is a generic seven-storey RC office building, whose plan is depicted in Fig. 3. Its interstorey height is 3.75m and the nominal thickness of a slab is 150mm. The dimensions of the internal and external columns are 400x400mm^2 and 400x250mm^2, respectively. The characteristics of the concrete and reinforcement steel are presented in Table 1.

Table 1: Characteristics of slabs and columns.

Element	Concrete				Steel
	Strength	Moisture content (%)	48mm permeability of (in m^2)	Cover in mm	∅ (in mm)
Slab	C37	3.8	$6.75 \cdot 10^{-17}$	20	12-16
Col.	C85	4.2	$1.92 \cdot 10^{-19}$	40	

4.3. Damage Scale

The damage scale adopted in this study is based on a visual qualitative scale proposed by the Concrete Society (2008), and described in Section 2.2. Owing to time constraints, the expert elicitation workshop focused on three damage states: defined as ds_1, ds_2 and ds_4. In addition, the experts decided to quantify the structural response measures only for the slabs and columns, since these were considered the elements whose performance is more critical during and after a fire. The current paper concentrates on a damage scale for RC slabs.
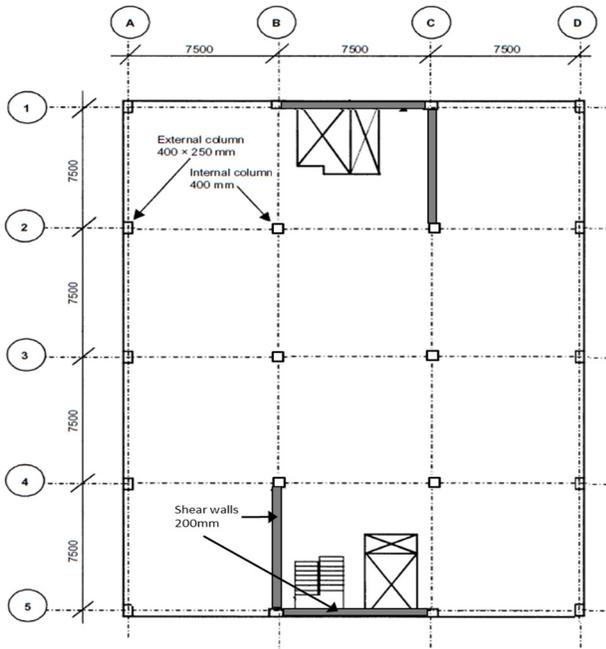

Figure 3: Plan of generic RC office building.

4.4. Structural Response Measures

The qualitative descriptions of expected damage and associated repair level of each damage state are related with four structural response measures. In particular, the experts were asked to provide their judgment on:

- The percentage (%) of the exposed surface area of a given element which would show signs of spalling such that it could be classed in a given damage state.
- The level of deflection, D, after cooling, which would be associated with a given damage state, in terms of:

$$D = \frac{L}{X} \qquad (1)$$

where L = is the length (span) of the element; X = is a parameter which determines the deflection in the mid-span on a slab and the end point of a column.

- The percentage of the residual capacity of the examined element that can be associated with ds_i, assuming that the element sustains no other structural damage, i.e., spalling or deformation. Note that the residual capacity is measured in terms of axial load capacity for columns and flexural capacity for slabs.
- The reinforcement bar temperature (in ^{o}C) associated with ds_i, again in the absence of spalling.

4.5. Expert elicitation workshop

The experts were invited to participate in a one-day workshop, which was divided into two sessions. During the morning session, each expert assessed the uncertainties associated with 16 seed variables by providing values corresponding to the 5%, 50% and 95% probabilities of being reached in a given scenario. While these variable realizations were known to the facilitator, the experts were not expected to know the precise values, but were expected to be able to provide credible ranges that captured the real values as closely as possible.
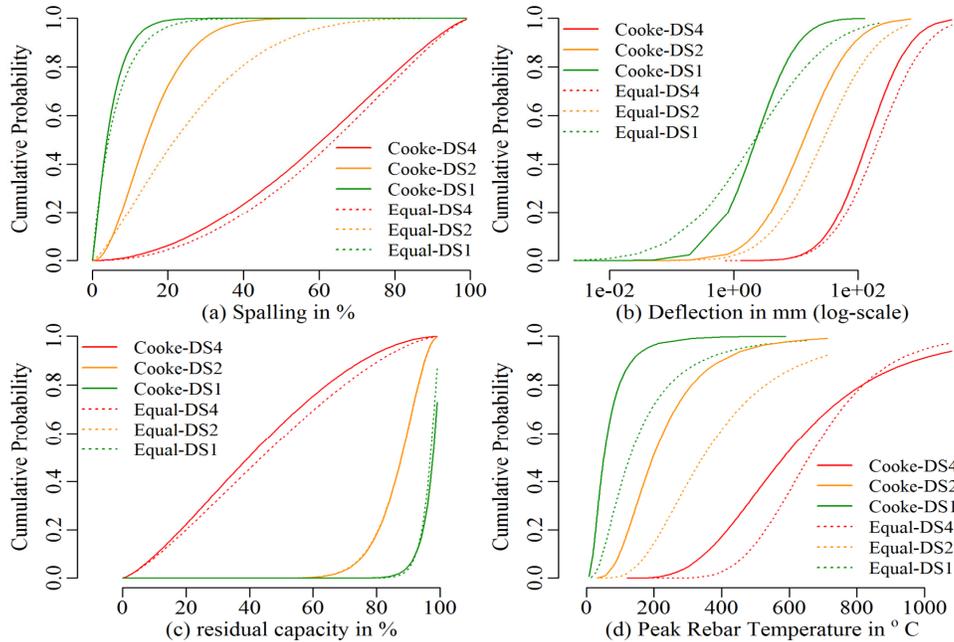
Figure 4: Cumulative probability functions for the four measures of structural performance for the three damage states using Cooke's and Equal weighing to pool the experts opinions.

The questions covered a wide range of issues, including: (a) general fire loss estimation questions, (b) the structural performance of RC structural elements in fire, (c) the development of fire in a compartment, (d) the material properties of fire-exposed RC and steel. To encourage experts to state their own independent judgments, responses to these seed questions were received and processed confidentially by the facilitator.

In the afternoon session, the experts were invited to provide their uncertainty judgments on the 'target' questions, assuming that the whole 1st-floor area of the generic RC building (in Fig. 3) was uniformly exposed to fire. Overall, twelve target questions were posed to characterize factor uncertainties for this problem.

4.6. Structural response-to-Damage relationship
The experts' responses were used as inputs into EXCALIBUR (Cooke and Solomatine, 1990), a software package for structured expert judgment elicitation. The weights for each expert are estimated according to the Classical Model and the empirical cumulative distributions of the

thresholds of the four structural response measures corresponding to the three selected damage states were produced.

However, EXCALIBUR is a generic tool and cannot recognize that some variables are non-negative, or others may have strict upper bounds (e.g. 100%). To create an empirical distribution that completely spans a set of expert responses with different, varying credible interval bounds, EXCALIBUR needs to calculate tail extensions beyond the lower and upper quantiles (in this case 5th and 95th percentiles), termed the 'intrinsic range' (Cooke, 1991). In doing this, sometimes the program returns small negative values at very low quantiles for non-negative measures, i.e. spalling and residual capacity. For such cases, resulting distributions can be post-processed to constrain them to positive values.

An additional distribution structure constraint is imposed to ensure that the three curves retain the expected relative ordering over their whole cumulative distributions, i.e., to avoid the curves overlapping or crossing one another at particular percentiles. For example, for

spalling damage all percentiles of ds_1 are constrained to be lower than those for ds_2, and ds_4 quantiles are constrained to be higher. This has been achieved by conditional re-sampling of the EXCALIBUR output distributions with the necessary constraint(s).

The resulting empirical cumulative distributions are then fitted to the two continuous cumulative distribution functions (cdfs) presented in Section 2.4, according to the characteristics of each variable. In particular, the distributions for spalling and residual capacity are fitted to beta distributions and the deflection and peak rebar temperature are fitted to lognormal distributions. The fitted distributions are shown in Fig. 4. The curves evidence the expected shape, e.g. the cdf of spalling for ds_1 falls to the left of the other two curves, indicating the smallest overall level of spalling. Similarly, the cdf of the ds_4 appears to the right of the other two, indicating a larger overall percentage of spalling than ds_2 or ds_1. The mean values of the thresholds for the three damage states and the width of the 90% confidence intervals of each distribution are also presented in Table 2.

It is noteworthy that uncertainty in the thresholds is greatest for all four structural response measures for ds_4, and smallest for ds_1. This is expected given the difficulty in predicting the structural performance of an RC slab that sustains such severe damage. As the length of a fire increases, the influences of a number of uncertain parameters increase, and hence the overall uncertainty around the structural damage also increases. Structural damage experienced in very long fires is apparently extremely uncertain and opinions may range from very little damage to structural collapse. This highlights the profound uncertainties within the structural fire engineering community as to the effects of fires on systems of structural elements (i.e. in real buildings), rather than on isolated structural elements in standard furnace tests (i.e. in regulatory/compliance tests).

In general, for a complex and uncertain problem like this one, if a single expert is asked to provide their judgment around the expected value of a variable and to quantify the uncertainty value, they typically provide an unreliable estimate of the mean and small uncertainty, expressed here in terms of the width of the 90% credible interval. By contrast, if a large group of experts is elicited and their opinions are weighted equally, a good mean estimate of the variable is typically obtained, but the associated uncertainty is very wide. Cooke's Classical Model offers a rational quantification of parameter uncertainty by optimized weighting of experts according to their ability to quantify uncertainty around variables. Generally, although not always, this produces an outcome distribution with formally quantified uncertainty that falls somewhere between these two extreme alternatives. In Table 2, it is clear that for five cases, the mean values of the thresholds obtained with Cooke's weighting scheme are close to their counterparts obtained for the equal weighting scheme (difference <10%). For four of these cases (i.e., the level of residual capacity corresponding to all three damage states and the level of spalling associated with ds_4), the width of the 90% confidence intervals obtained by Cooke's weighting scheme is close (difference <10%) to the ones obtained by the equal weighting scheme. Thus, for these four cases, the pooled opinions of the best-weighted experts do not differ substantially from the aggregated opinions of all thirteen experts. This indicates that the community cannot constrain these relationships with current knowledge and understanding, and further research is needed to gain a deeper insight. Similar conclusions can be drawn for the fifth case, where the 90% confidence interval width for the level of peak reinforcement bar temperature for ds_4 based on Cooke's weighting is larger than for the equal weighting case; it may be there are more complexities to consider than are accommodated

Table 2: The mean and the width of the 90% confidence intervals together with the differences between the values based on Cooke's and equal weighting.

RS	DS	Cooke		Equal		Diff. (in $1-X_{Equal}/X_{Cooke}$ %)	
		mean	*90% range*	*mean*	*90% range*	*mean*	*90% range*
Spalling (in %)	ds_4	59	76	62	73	-5%	3%
	ds_2	16	29	25	55	-60%	-88%
	ds_1	5	13	6	18	-22%	-36%
Deflection (in mm)	ds_4	312	1093	579	2156	-86%	-97%
	ds_2	39	147	104	398	-165%	-171%
	ds_1	5	17	27	87	-452%	-407%
Residual Capacity (in %)	ds_4	42	77	45	81	-8%	-6%
	ds_2	87	24	87	25	0%	-2%
	ds_1	97	10	96	9	0%	10%
Peak Rebar Temp (in ^{o}C)	ds_4	631	819	681	576	-8%	30%
	ds_2	229	403	393	653	-72%	-62%
	ds_1	68	163	172	419	-152%	-156%

by the present basic framing of the related elicitation question.

With regard to the remaining thresholds of structural response measures, the mean values produced by Cooke's weighting scheme are systematically smaller than those obtained for the equal weighting scheme. Similarly, the width of the 90% confidence intervals is also substantially reduced. This is illustrated in Fig. 4, where the cdfs for these thresholds appear to be shifted to the left. This indicates that the pooled opinions of experts using performance-based weights appear to be more conservative in the determination of the mean – and hence likely damage state – than implied by simple equal-weight aggregation of the views of the whole group of experts.

5. CONCLUSIONS

A fire damage scale relevant to RC slabs of a typical modern, open-plan, mid-rise concrete cast in place frame is produced in this study. Expert elicitation is adopted in order to determine the thresholds of four response measures to three damage states. Areas of future research include the spalling and peak rebar temperature thresholds at ds_4 and the residual capacity thresholds for all three damage states. The next step will be the determination of thresholds for the other structural elements, i.e., the columns, walls, and beams. However, additional research

is also needed to move from this rudimentary scale, which is concentrated to the assessment of damage to individual members, to a global damage scale that can assess the overall system performance of a building and therefore be able to credibly and quantifiably assess the possible losses due to fire.

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