TOWARDS SMART FIRE-RESISTANT CONCRETE BUILDINGS: AN INTERNET OF THINGS (IoT) BOOSTED STRATEGY

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Abstract. *The Internet of Things (IoT) constitutes one of the most recent technical advances believed to have profound implications to future natural and built environments. This paper discusses the potential of the IoT in the area of reinforced concrete (RC) structures. In particular, the application of the IoT to in-service RC buildings for improved fire safety is examined. The paper proposes a conceptual framework towards next-generation smart fire-resistant concrete buildings and identifies four key components that are essential to its successful realization. Indeed, owing to the fast-changing nature associated with a concrete building under fire, the fruition of the framework first and foremost rests upon timely information communication with respect to the actual structural condition of the building when a fire situation is ongoing. Also, as in most cases it is the in-service buildings, as opposed to those newly constructed, that are subjected to fire accidents, mechanisms need to be featured so that the corresponding up-to-date structural health condition can be allowed for appropriately. Other factors to be considered include the adequate constitutive description capturing the very stress-strain relations on this occasion and the final statistical damage prognosis which is intended to provide on-the-spot advice as to how the firefighting resources can be optimally allocated and what the best plan is for evacuation of people and equipment. The paper ends with some concluding remarks outlining relevant challenges and future work in regard to enhanced fire-resistance performance of IoT boosted smart RC buildings.*

1 INTRODUCTION

The design of reinforced concrete (RC) buildings for fire resistance has long been one of the well-established industry routines. In terms of maintaining the structural adequacy, as per the current state of practice[1], the dimensional and detailing requirements are often imposed during the design. For example, in order for a continuous beam with the cross-sectional dimension of 150 mm by 300 mm to achieve a fire resistance period of 90 minutes, a minimum value of 35 mm must be satisfied by the average axis distance of the longitudinal rebars, which is defined as the rebar area (or the product of the rebar area and the rebar characteristic strength where appropriate) weighted average center-to-nearest-exposed-surface distance of the longitudinal rebars involved. Also, for flat slabs it is required that the slab thickness and the distance between

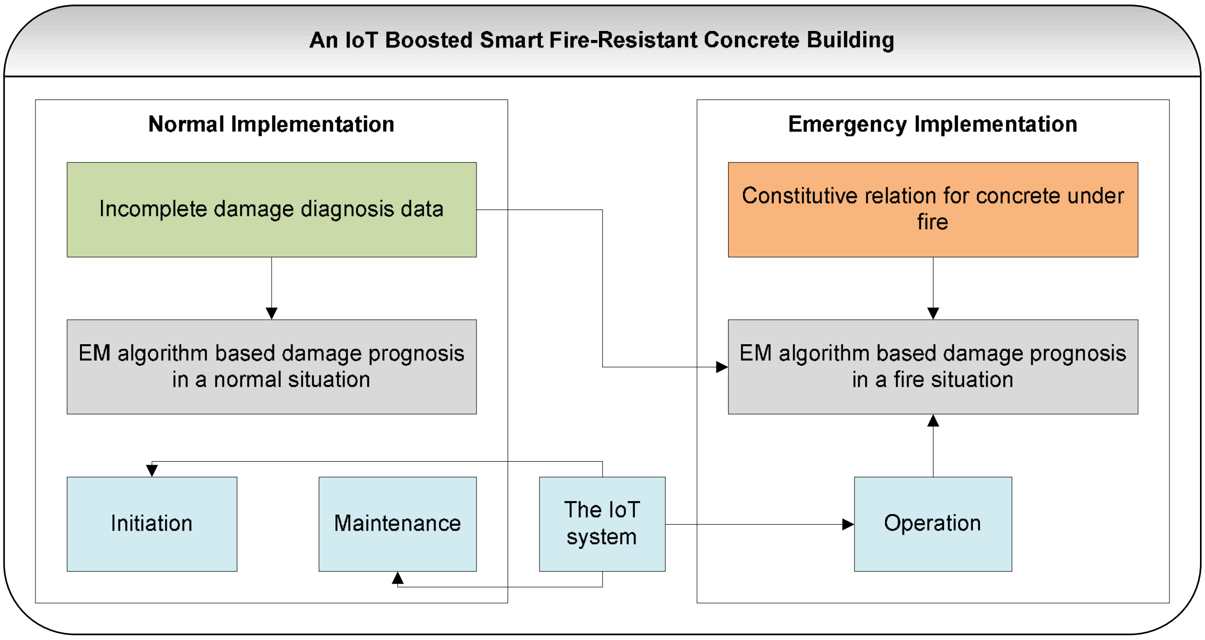

Figure 1: Proposed conceptual framework for the IoT boosted smart fire-resistant concrete buildings.

the lowest-layer rebar center and the corresponding nearest exposed surface be at least 180 mm and 15 mm for a fire resistance period of 60 minutes and 200 mm and 35 mm for a 120-minute period, respectively.

Effective as these types of design codes specified clear-cut requirements may prove to be on many occasions in ensuring that RC buildings fulfill their expected fire-resistant load-carrying capacity, when looking at a building subjected to an ongoing fire situation, the firefighters, building owners and building occupants would probably be more interested in having a more dynamic picture on what exactly is happening especially to those critical structural members in the building and how things would be most likely to evolve. Appreciating the unique flair of smart structures[2] in this regard, this paper is concerned with exploring the potential of an emerging technical advance known as the Internet of Things (IoT)[3,4] to enhance the fire-resistant capacity of RC buildings.

2 CONCEPTUAL FRAMEWORK

The conceptual framework of the proposed IoT boosted strategy for smart fire-resistant RC buildings is illustrated in Figure 1. Essentially, there are two kinds of implementation module featured in the framework, viz. the normal implementation and the emergency implementation. The normal implementation happens on an everyday basis when no fire accident is present. Its primary objective is to keep monitoring the health condition of the RC building in question and pass the relevant information known as the damage diagnosis data on to the emergency implementation module, which will be activated in due course when a fire accident occurs. Apart from this, the normal implementation module can also yield a useful by-product: From the up-to-date health condition information, damage prognosis can be made as to how probable the RC building may fulfill its original design expectations in a normal situation.

The emergency implementation module, on the other hand, aims at capturing the time-variant probabilistic characteristics exhibited by an RC building in a fire situation. To this end, in addition to the damage diagnosis data passed on from the normal implementation module, it is also indispensable to stream into the relevant safety evaluation system the information pertaining to the ongoing fire, such as the temperature distribution within the building which undoubtedly changes quickly as the fire condition evolves. This can be achieved through an appropriately preconfigured IoT system. Indeed, an IoT system can be designed, constructed, and maintained as part of precautions against fire; when a fire accident does happen, the IoT system begins to operate and helps to gather information needed for the damage prognosis. Note that, unlike its

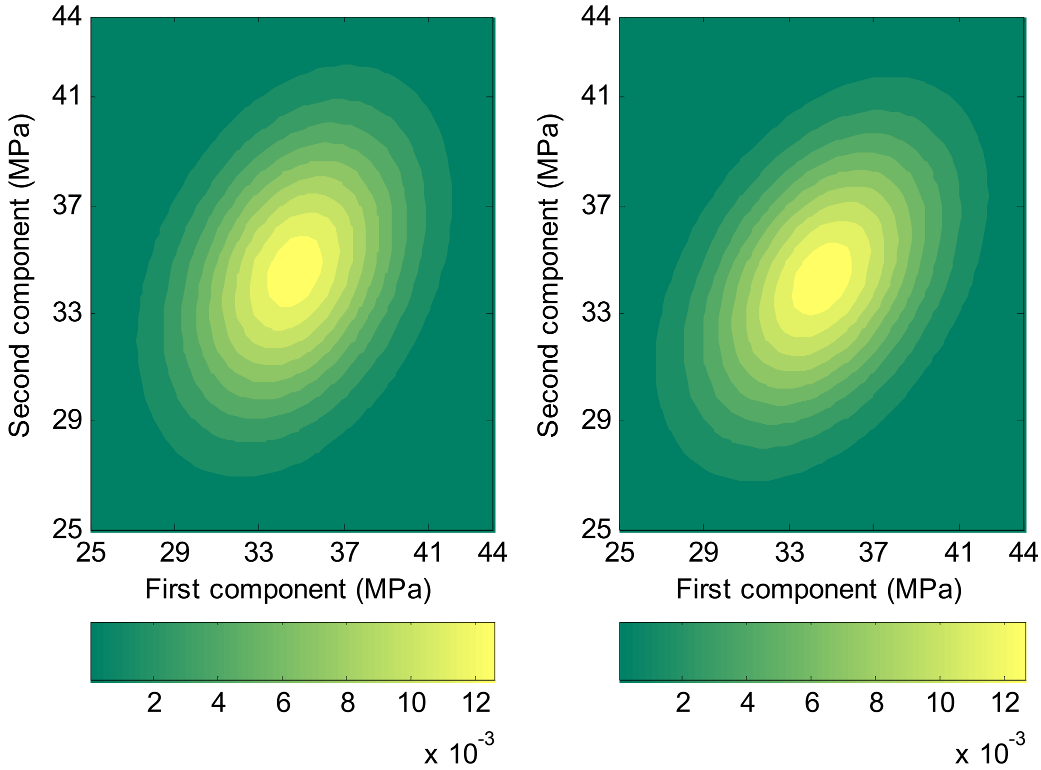

Figure 2: Contour plots for the estimated joint probability density functions of the concrete cylinder compressive strengths in the complete- (the left subfigure) and incomplete-data (the right subfigure) scenarios.

counterpart in the normal implementation module, the damage prognosis in the emergency implementation module refers to the predictions about the safety performance of an RC building in an ongoing fire situation and is typically with respect to a time frame of several hours. Needless to say, a suitable description of the constitutive relation between the concrete stress and strain in a fire situation is required as well.

The key components of the proposed framework are delineated in more detail in the subsequent four sections.

3 KEY COMPONENT #1: POTENTIAL OF THE IoT IN STRUCTURAL ENGINEERING

As briefly alluded to before, when an RC building is in an ongoing fire situation, it is imperative to find out, as efficiently as practical, what the actual structural condition of the building is currently like and how the structural condition would be most likely to evolve. This essentially relates to the following three aspects: sensing, communication, and processing. Sensing is to gather adequate information in order to generate a faithful description of the temperature distribution within the building. For obvious reasons, the sensors needed should be installed prior to the eruption of the current fire. Once the relevant information on the temperature distribution is captured, it is also necessary to set up an appropriate channel through which the information can effectively be communicated to a processing system. Subsequently, it is in the processing system that the communicated information, in combination with any existing structural diagnosis results, is analyzed, leading to the final structural prognosis results. Owing to the central role that the processing system is expected to play, locating it in a relatively safe place (e.g. a fire station in the neighborhood or a firefighting vehicle coming to the fire site) would be desirable.

Basically, the whole process involves a series of objects, viz. the structural elements in the building such as beams, columns, walls, slabs and joints, sensors for the temperature data acquisition, and the objects forming the processing system. In this context, the IoT paradigm[3,4] would help create an opportunity whereby these individual objects are somehow interconnected with one another to achieve efficacious information flow. As illustrated in Figure 1, for an in-service building, an IoT

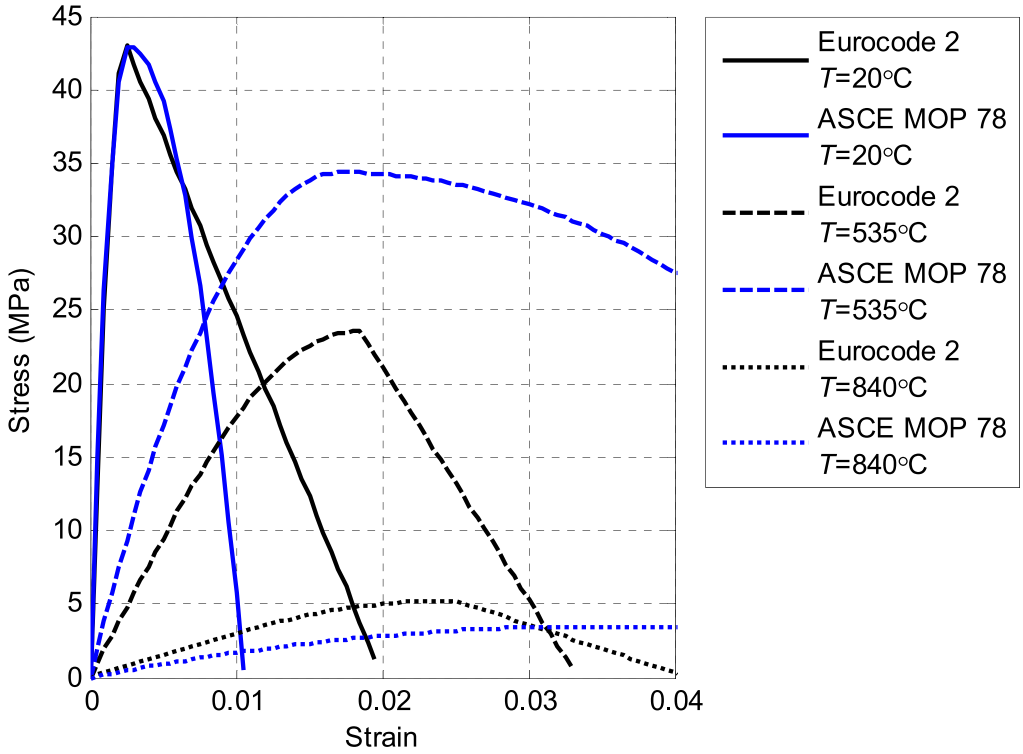

Figure 3: Comparison between different constitutive relations as regards concrete in high-temperature conditions.

system will first be initiated and then be maintained on a regular basis in the normal implementation module; when the emergency implementation module is invoked, it starts to operate in such a way that the information indispensable for obtaining relevant damage prognosis is communicated appropriately. The remit of such an IoT system can even be extended to the accouterments carried by each individual firefighter for improved risk management.

4 KEY COMPONENT #2: DEALING WITH IN-SERVICE CIVIL STRUCTURES

The proposed IoT boosted smart RC buildings are to exhibit improved fire-resistant performance during their service lives. Typically, after an RC building is constructed and put into use, there exist various factors that may adversely affect its structural integrity, load-carrying capacity, or serviceability. At the time when a fire accident occurs, the actual structural health state of the building can differ significantly from its original one. Accordingly, ascertaining the current structural health state, which is known as damage diagnosis, becomes very important to the subsequent task of generating reliable damage prognosis data. Despite the continuing advances in the area of damage diagnosis, it is, however, not uncommon in reality that only incomplete damage diagnosis data turn out to be available. For the purposes of the related damage prognosis, the data missingness of this kind can be effectively dealt with following some recently developed formulations[5] where a statistical methodology, viz. the expectation-maximization (EM) algorithm[6,7], is applied. As an example, Figure 2 shows the comparison between an estimated joint probability density function of two concrete cylinder compressive strengths in an incomplete-data scenario and its complete-data-scenario counterpart. In the incomplete-data scenario herein, some of the data constituting the damage diagnosis results are assumed to be missing completely at random[8]. Despite the data missingness, the incomplete-data-scenario estimated joint probability density function seems to agree fairly well with that in the complete-data scenario. Indeed, the estimates of the means of the two concrete cylinder compressive strengths are respectively 34.7 MPa and 34.6 MPa in the complete-data scenario and 34.6 MPa and 34.3 MPa in the incomplete-data scenario, and the estimates of the covariance

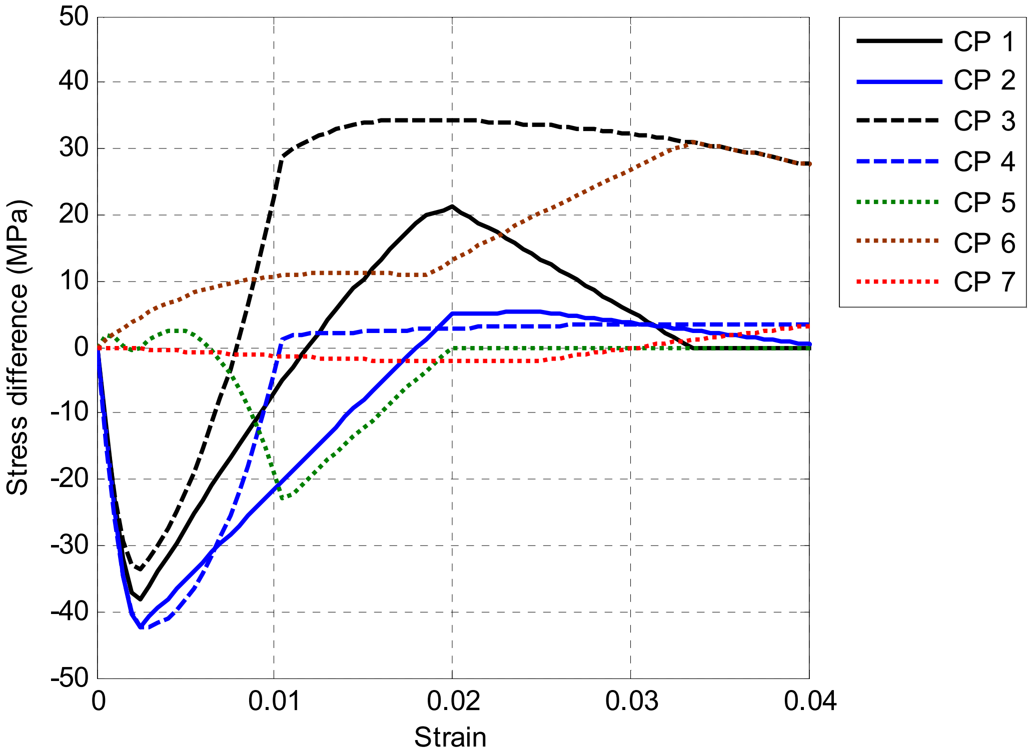

Figure 4: Stress differences between the comparison pairs (CP1: Eurocode 2 and *T*=535°C vs Eurocode 2 and *T*=20°C; CP2: Eurocode 2 and *T*=840°C vs Eurocode 2 and *T*=20°C; CP3: ASCE MOP 78 and *T*=535°C vs ASCE MOP 78 and *T*=20°C; CP4: ASCE MOP 78 and *T*=840°C vs ASCE MOP 78 and *T*=20°C; CP5: ASCE MOP 78 and *T*=20°C vs Eurocode 2 and *T*=20°C; CP6: ASCE MOP 78 and *T*=535°C vs Eurocode 2 and *T*=535°C; CP7: ASCE MOP 78 and *T*=840°C vs Eurocode 2 and *T*=840°C).

between the two are 4.3 MPa^2 and 5.4 MPa^2 in the complete- and incomplete-data scenarios, respectively.

5 KEY COMPONENT #3: CONSTITUTIVE CONSIDERATIONS OF CONCRETE UNDER FIRE

Effective predictions on the safety performance of an RC building exposed to fire rely on the availability of an adequate structural model that can faithfully describe the behavior of the building, making due allowance for the effect of fire. Typically, the structural model as such needs to consider three aspects: equilibrium requirements, constitutive relations, and geometric conditions. In the equilibrium requirements, the relations among the forces, moments, and stresses in the structural members of the building are stipulated. The constitutive relations capture the inherent laws that, under fire conditions, characterize the interaction between the stresses and strains of the materials involved, i.e. concrete and steel. Meanwhile, the geometric conditions are to prescribe the relations between the strains and the displacements for the structural members being considered.

Of particular interest herein is the constitutive relation for concrete under elevated temperatures. In fact, the constitutive relation for a given type of concrete differs with respect to the temperature at which it is examined. The changes in the constitutive relation of concrete of this kind have been documented in relevant building codes and manuals, such as Eurocode 2[9] and American Society of Civil Engineers (ASCE) Manual of Practice (MOP) 78[10]. Although these documents all appreciate that the constitutive relation varies with the temperature, no apparent consensus seems to have been developed on the exact mode by which the temperature affects the constitutive relation. Take normal-weight concrete made of siliceous aggregate as an example, and assume that the concrete has a cylinder compressive strength of 43 MPa at the temperature *T* equal to 20°C. Figure 3 compares the corresponding stress-strain curves

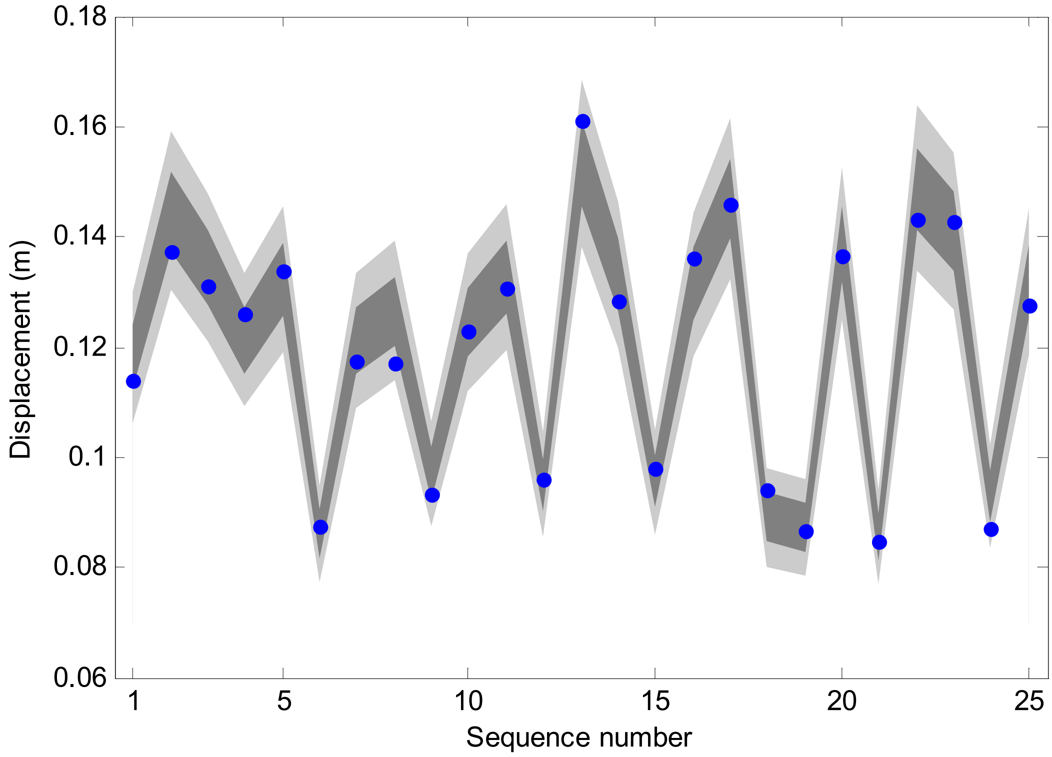

Figure 5: Quality assurance for the surrogate model where the solid blue dots denote the output of the surrogate model, and the dark and light gray belts mark the intervals with a relative error of 5% and 10%, respectively.

respectively obtained as per Eurocode 2 and ASCE MOP 78 when T is equal to 20°C, 535°C, or 840°C. The differences between these curves are highlighted through seven comparison pairs (CPs) in Figure 4. As can be seen from Figures 3 and 4, even at exactly the same strain and temperature levels, the stress according to ASCE MOP 78 can sometimes vary considerably from that based on Eurocode 2. As far as the structural model mentioned at the beginning of this section is concerned, this entails either some calibration work to ascertain the constitutive relation that in some sense best describes the concrete exposed to the elevated temperatures in question or a sensitivity study whereby the implications of the differing stress values can be evaluated quantitatively.

6 KEY COMPONENT #4: STATISTICAL DAMAGE PROGNOSIS

The statistical damage prognosis herein is to predict, premised upon the pertinent damage diagnosis data which can sometimes be incomplete, the safety-related structural behavior of an RC building exposed to fire. As such, the typical time frame with respect to which the prediction is to be made is up to several hours only. This creates a challenge for the structural modeling involved and in particular the time integration procedure in the structural modeling: Successful as many canonical time-marching schemes are in solving the corresponding governing differential equations, when it comes to the damage prognosis task at hand, they may on many occasions become unsuitable owing to the long calculation time. After all, for the current application, the time integration procedure often needs to be repeated hundreds or even thousands of times. In contrast to grappling to find a more efficient scheme for the time marching, an alternative is to bypass it. In fact, this has been achieved in a cognate situation where the time integration for a nonlinear two-story RC shear frame subjected to hazardous earthquake ground motion was performed through an appropriate artificial neural network based surrogate model[11]. It should be emphasized that the quality assurance pertaining to the model surrogation of this kind is essential, and the quality assurance can effectively be implemented by comparing the output of the surrogate model with that resulting from the time marching. Figure 5 gives an example of the comparison, where the surrogate model generated values of the maximum

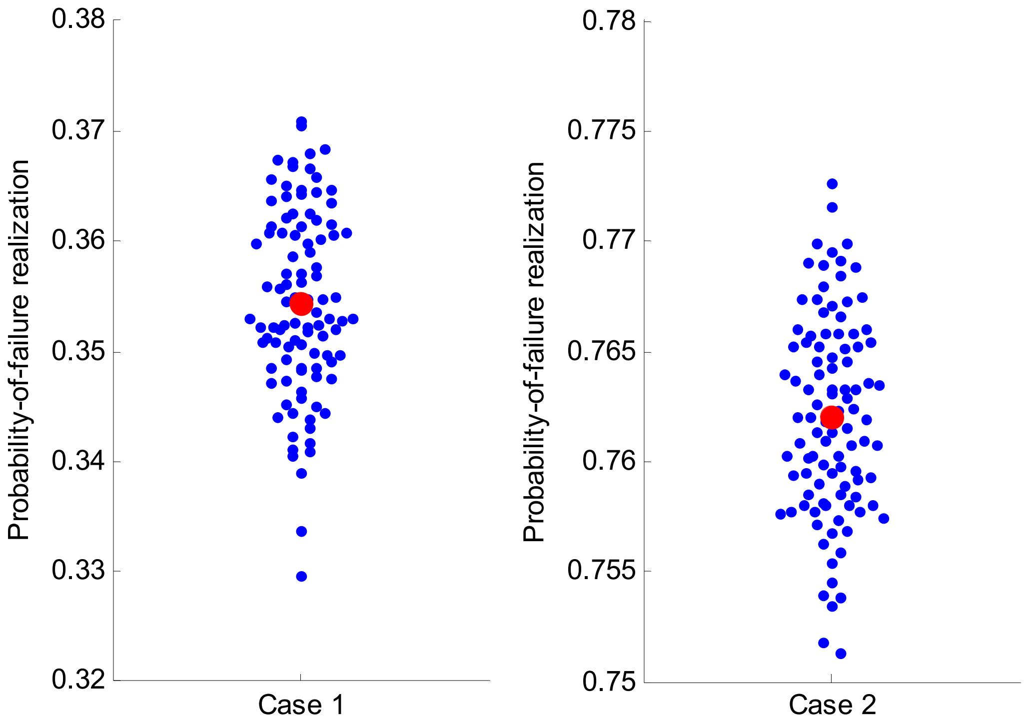

Figure 6: Realizations of the probability of failure of an RC system corresponding to different time spans (small blue dots: probability-of-failure realizations; large red dots: sample means of the respective realizations in the two cases).

interstory relative displacement of the aforementioned nonlinear two-story RC frame are plotted together with the corresponding intervals derived from the time marching. Once the quality assurance is satisfactorily fulfilled, the surrogate model can be used in place of those less efficient time-marching schemes for the subsequent damage prognosis. There exist multiple formulations as to how the damage prognosis for an in-service RC structure can be carried out. Probabilistically quantifying the likelihood of the situation where the structure fails to meet a given structural performance criterion is one of them. As an example, Figure 6 visualizes the probability-of-failure samples obtained for an RC system with respect to a time span of 75 (Case 1) and 125 (Case II) units, and the full details of this example are documented in the relevant literature[5]. The formulation of this kind can be readily extended to perform damage prognosis for RC buildings exposed to fire. The advantage of this formulation is that it provides the flexibility in selecting the structural performance criterion that best suits the specific scenario being considered.

7 CONCLUDING REMARKS

The induction of the IoT paradigm has created opportunities to engender and facilitate information flow among the interconnected objects. This would have huge implications to strategies aiming at improving the fire-resistant performance of RC buildings. A reliable, well-performing IoT boosted strategy for fire-resistant RC buildings should promote accurate and fast information gathering and processing and meanwhile feature indispensable remediation mechanisms in case of possible data missingness events happening to the relevant damage diagnosis. The former can be achieved by appropriate sensor deployment, suitable constitutive descriptions of the materials exposed to fire, and often a surrogate model[11] with superior efficiency for the time integration involved; the EM algorithm embedded formulations[5] provide an option for the latter. Finally, owing to both its mathematical rigorousness in quantifying the pertinent uncertainty and its flexibility in relating to various structural performance criteria, the probability of failure of a critical structural member in the RC building being considered constitutes a promising tool through which the damage prognosis results can be reported.

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