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Forensic education through causality quantification – a shift of paradigm

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ABSTRACT: A recent series of natural disasters have resulted in thousands of damaged structures in the world. As a result, there is a huge interest in developing forensic engineering curricula to satisfy the societal needs of validating claims and infrastructure rehabilitation efforts. However, forensic engineering relies heavily on experiences, professional judgements and, in contrast to other engineering practices, an inverse reasoning approach whereupon knowledge is accumulated from construction design and limited post-event observations. As a result, it is difficult to ensure that new graduates can perform quality investigations and event reconstruction. In this article, the authors attempt to address a possible shift of paradigm in forensic engineering education by suggesting the establishment of causality quantification such that investigative procedures can be standardised to reduce the *guess work* that is common in this rapidly developing and highly challenging field. This approach requires establishing a database with innovative uses of science-based tools such as the *West Point Bridge Designer* as illustrated in an example of causality quantification.

INTRODUCTION

Recent catastrophic events (Kobe, Northridge, Chi Chi and Armenian earthquakes, Hurricane Katrina, and the Asian tsunami) around the world have resulted in millions of damaged or destroyed homes and structures. The devastation to people's cultural heritage and the imposed human sufferings will take years – possibly generations – to recover.

A more immediate problem that faces many governments and international agencies is the need to address societal rehabilitation and infrastructure recovery. A key obstacle to these efforts is the validation of insurance claims. This could lead to social upheavals against the government in a worst case scenario. The proper and timely identification of fraud will reduce potential lawsuits and the pain and suffering of disaster victims, which can only be achieved by reliable forensic practices.

The ultimate goal for all forensic work should be to provide accurate event reconstruction and evidence finding that can substantiate a logical and valid conclusion to the case. Hence, the ability of forensic engineers to quantify the quality of forensic work would be an important service to the clientele and society at large. This ability should be fostered in current engineering curricula, so that young engineers will be able to conduct quality investigations early in their careers. Unfortunately, there has been little work undertaken in both the areas of forensic quantification and quality forensic education.

In this article, the authors review the current state of education in forensic curricula and propose a forensic quantification methodology. The authors demonstrate by example the potential of integrating forensic quantification into undergraduate study.

CURRENT FORENSIC PRACTICES AND EDUCATION

Forensic comes from the Latin word *forensus*, which means *of the forum*. As a profession, the single most critical feature that distinguishes forensic scientists from other scientists is the expectation of court appearances and testimonies that offer their opinions and findings. In general, forensic science is science exercised on behalf of the law in the just resolution of conflict [1]. However, forensic engineering has been defined as follows:

> *the application of engineering in the jurisprudence system requiring services of legally qualified professional engineers. Forensic engineering includes investigation of physical causes of accidents and other sources of claims and litigation, preparation of engineering reports, testimony at hearings in judicial proceedings, and rendition of advisory opinions to assist the resolution of disputes* [2].

Important elements for forensic work are professionalism, legal knowledge and the capability to provide expert solutions to judicial proceedings [3].

Forensic work investigates facts that provide the legal process with a doubt-free explanation of the causality for failures, which is typically an inverse engineering procedure, where knowledge is accumulated by post-event evidence finding [4]. This approach contradicts the typical scientific approach of generating statistically reliable data to validate causal hypotheses and relies on deductive reasoning with very little experimental support. Additionally, the lack of *in-between data* prompts a heavy reliance on an engineer's interdisciplinary expertise, training and reasoning ability. Therefore, current forensic practices often fail to produce complete multi-disciplinary solutions to complex forensics problems, resulting in unreliable forensic conclusions.

The National Society of Professional Engineering has addressed this unreliability issue as a national concern [5]. Cohen et al indicated several needs of the forensic engineering community that may improve current practices, including the collection of historical data, the establishment of in-situ monitoring techniques and the generation of experimental results [6].

Forensic failure analysis is a critical component of forensic study, but is often a neglected subject in most civil engineering educational programmes. This was reflected consistently in national surveys [7][8][9]. Most efforts in educating failure analysis at the undergraduate level are introduced through case study courses, various authors, such as: Rendon-Herrero, Pietroforte, and Fowler and Delatte have demonstrated the successful implementation of case studies in courses to help students appreciate the significance of learning from failed structures [10-12]. Since most engineering disasters (building collapses, out-of-design anomalies) are subject to forensic investigation by engineers experienced in forensic methods of investigation. Tools that are typically useful for forensic studies may include accident reconstruction, event re-enactment, code interpretations and failure analysis. Such investigations often go hand-in-hand with metallurgical and material science examination and with stress analysis.

However, case studies do not necessarily promote inductive reasoning and encourage the active use of analytical tools that undergraduate students are familiar with. Hence, a teaching method that provides a direct linkage between failure and actual causality can be more intuitive for students learning forensic investigation techniques. Such a method requires a significant shift of paradigm in forensic education: educators must be creative in developing realistic interdisciplinary tools to help students learn to establish causal relationships between system performance and failures.

FORENSIC QUANTIFICATION

To quantify causality, a statistically sufficient data set is sought so that numerical quantifiers can be assigned to each known causal relation. Castaneda et al and Kaggwa first suggested using fuzzy logic as probabilistic indices for causality investigations [13][14]. Chen et al subsequently introduced the notion of quality forensic practice through probabilistic quantification [15]. It is obvious that such an approach requires the causality relationships for a certain failure type to be well-defined with statistically sound failure cases. A large dataset is available for structural component failures (eg through laboratory testing); however, documented failures of complex structural systems are rare and non-causal. Hence, establishing inductive reasoning through hypotheses validation with experiments and modelling is essential to the proposed forensic quantification.

The probability of identifying causality is defined as:

$$P(a_i) = P(A_{mi} > 0 \mid A = a_i) \tag{1}$$

where a_i is damage outcome due to a specific causal relation i. A_{mi} is the measured outcome and A is the actual outcome. If a delta function is specified as:

$$\delta(k_j) = \begin{cases} 1 \sim \text{when causality exists} \\ 0 \sim \text{otherwise} \end{cases} \tag{2}$$

then the actual causality probability a_i with specific weighting coefficients b_i can be differentiated from unrelated causalities k_j with weighing coefficients z_j as (with an error term ε_j):

$$P(a_i)_m = \sum_{i=1}^{p} b_i a_{mi} + \sum_{j=1}^{q} z_j \delta_j(k_j) + \varepsilon_j \tag{3}$$

If adequate data or case studies are available, they can be fused and integrated to explain causality. This process, although initially difficult and time-consuming, can be streamlined with accumulated knowledge. To ensure positive causality, the squared sum of the residuals S is utilised:

$$S = \sum_{m=1}^{n} \left[P(a_i)_m - \left\{ \sum_{i=1}^{p} b_i a_{mi} + \sum_{j=1}^{q} Z_j \delta_m k_j \right\} \right]^2 \tag{4}$$

Likely causality can be established by optimisation relative to the weighting functions, thus:

$$\frac{\partial S}{\partial b_i} = 0 \tag{5}$$

$$\frac{\partial S}{\partial z_j} = 0 \tag{6}$$

In the cases where limited data are available, additional data can be generated using extensive structural modelling and numerical simulation. If standard procedures can be established to ensure consistent data generation, then positive causality can be established for a wide variety of problems. The proper scientific procedures for a true experiment-based investigation typically involve the following steps:

- Observe structural failures;
- Establish parameters for reproduction;
- Establish failure hypotheses;
- Construct structural replicas;
- Make failure predictions based on hypotheses;
- Test predictions by experiments on models;
- Repeat the above steps [16].

EXAMPLE OF EDUCATION IMPLEMENTATION

To demonstrate the causality calculation, an undergraduate student is engaged in independent study as a summer research project using the *West Point Bridge Designer* to generate data for a 21-member truss bridge to determine the possible failure modes under the traffic crossing of a single standard AASHTO H20-44 truckload [17]. This example is used to determine the causal relations for the failure of a complex system. Typical failures of a structural system may be due to one of four reasons: over-loading, inadequate capacity, environmental-induced damages and boundary condition changes.

By limiting the problem to a single truckloading case, this example demonstrates the possible failure modes as a function of structural members. Figure 1 shows how the bridge members are numbered in this study. The problem is further limited to constant material types (A 36 steel bridge members). So the only variable is the different member cross sections.

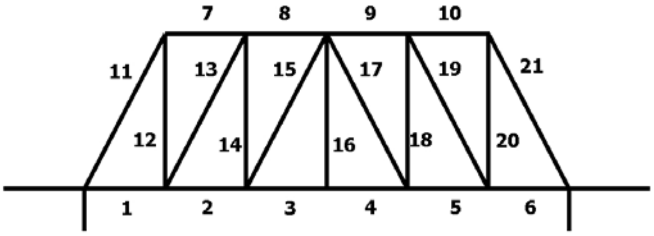

Figure 1: Bridge member numbers.

West Point Bridge Designer (WPBD) is a popular program to educate students about the process in structural. The software realistically simulates metal bridge component behaviour using a moving truck-load and basic truss analysis procedures. The software assigns unit costs to construction, labour and materials; hence, students can learn about the economics of bridge design. The authors have used the software as an instructional tool in undergraduate structural analysis classes. Figure 2 shows the WPBD program with the standard truck crossing over the bridge and caused the bridge failure. The members under high stresses are at the front of the image.

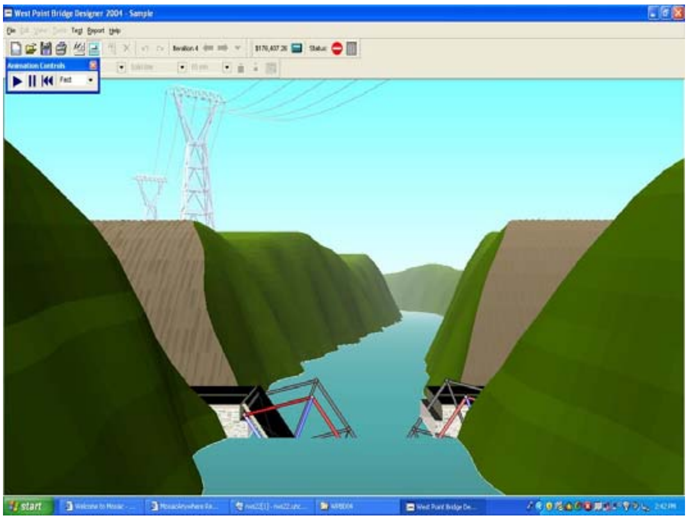

Figure 2: WPBD showing failed bridge during truck crossing [17].

The goal of the undergraduate research is to establish the failure probability for each member of the 21-member bridge and establish a most probable failure cause for the bridge. Figure 3 presents a probability tree for a failure calculation. The undergraduate student was asked to perform a Monte Carlo simulation using randomly generated members and their corresponding section properties. The selected members and material properties were then input into WPBD to generate fail/not fail scenarios. The total span of the bridge was 24 m long. The original design consisted of members of 120 mm × 120 mm cross-section, except for members No. 11 and 21, which have 140 mm × 140 mm cross-sections. The cross-sections are limited to a 10 mm × 10 mm to a 140 mm × 140 mm range. A total of 207 simulations were conducted for this example problem.

In this study, the individual member stiffness is the only variable and is, therefore, the only possible cause of failure. Since section stiffness reduction for a member is independent to other members, the weighting coefficient b_i is considered 1 for all damage cases. Likewise, for the non-causal terms, coefficients z_j and errors ε_j are considered zero. Thus, the residual S calculation is greatly simplified. Table 1 shows the outcome failure probability for each of the members (Column 3).

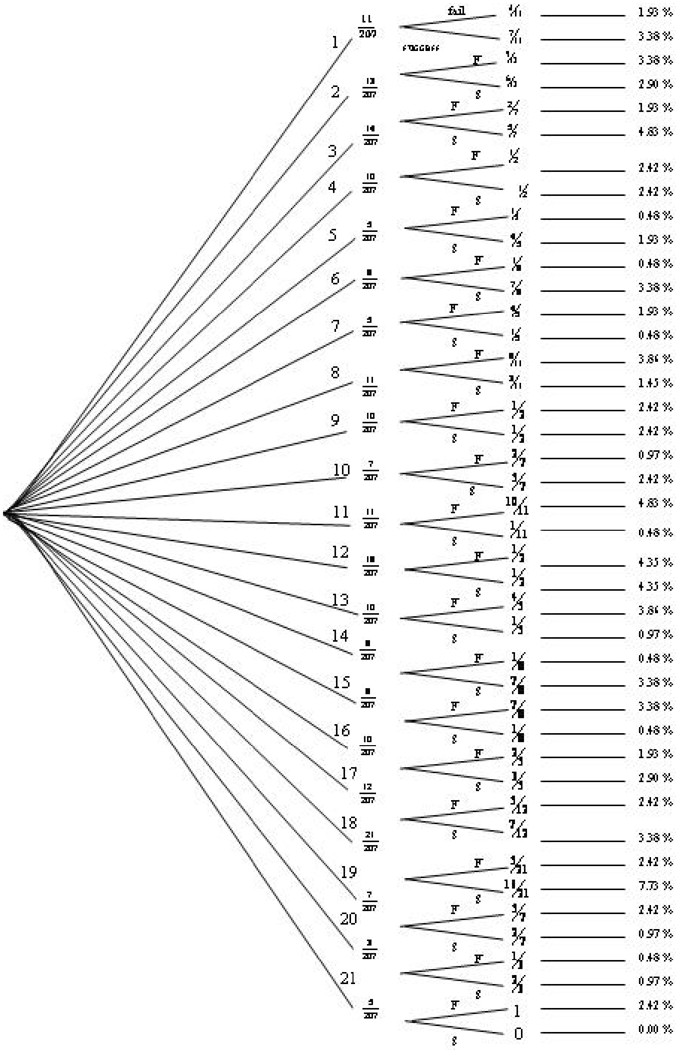

Figure 3: Probability tree for a failure calculation.

Table 1: Failure probability for each bridge member.

Mem	No. Occur.	Failure Outcome	Causality Probability	Square Sum Residuals S	% Ratio/ Total S
1	11	4	0.364	105.5	4.89
2	13	7	0.538	102.0	4.73
3	14	4	0.286	107.1	4.97
4	10	5	0.500	102.8	4.76
5	5	1	0.200	108.9	5.05
6	8	1	0.125	110.5	5.12
7	5	4	0.800	96.8	4.49
8	11	8	0.727	98.2	4.55
9	10	5	0.500	102.8	4.77
10	7	2	0.286	107.1	4.97
11	11	10	0.909	94.6	4.39
12	18	9	0.500	102.8	4.77
13	10	8	0.800	96.8	4.49
14	8	1	0.125	110.5	5.12
15	8	7	0.875	95.3	4.42
16	10	4	0.400	104.8	4.86
17	12	5	0.417	104.4	4.84
18	21	5	0.238	108.1	5.01
19	7	5	0.714	98.5	4.57
20	3	1	0.333	106.2	4.92
21	5	5	1.000	92.9	4.31

Since causality is defined as a function of the bridge members, causality probability is calculated for each member. Member 21 is shown to be the most probable member to fail. However, expressing S as a percentage of the total S for the system, the small standard deviation of the percentage S values for all members indicates that they have nearly an equal likelihood of failure, which is expected for this simple scenario. The accuracy of the causality study will improve as more data sets become available.

DISCUSSION

The above example demonstrates how computer simulations can be used to teach undergraduate students failure analysis and causality quantification. Through a Monte Carlo simulation, students see which member of a particular type of truss bridge is most likely to fail. This approach can be extended to any structure type or analysis. Students can then apply this knowledge into actual forensic investigations to determine the most probable failure causes for any system type. For actual forensic investigation, students can assign reasonable weighing coefficients to each causal relation. Computer simulation is not the only approach to systematically generate database: Chen et al suggest the use of massive scaled structural models or replicas for generating more failure data [15]. This contrasts to traditional forensic education using case studies; students can use this newer approach to delineate the probable causes of failure to unrelated causalities.

Good forensic engineering practice demands a reasonably good relationship between failure and its causes; the proposed approach represents a significant shift in the forensic education paradigm in that a true scientific-based investigation that relies on the generation of a statistically sound sample population of failure cases is established. The outcome of this investigation should be supported with strong evidence that is supported by not only logic, but also scientifically sound quantifiers. While real-life failure data are scarce, forensic quantification studies can be conducted using structural modelling. It should be recognised, however, that the proposed approach is more difficult to implement for structures with parameters that may be unknown or unquantifiable.

Some additional reasons why experimentally-based studies may be difficult to implement in forensic engineering curricula are as follows:

- Most systems are difficult to define;
- Few systems are simple enough to reproduce for repetitive experiments;
- No universal monitoring instrumentation that allows synchronised multiple-level sensing and automated data fusion is available currently.

CONCLUSIONS

To promote quality forensic engineering practices (education), the authors suggest causality quantification using probabilistic indices from the generation of a large statistically-sound data base. An example of curricular implementation is described where the *West Point Bridge Designer* has been used in undergraduate research to generate 207 failure cases of a truss bridge. Causality quantification is then studied for each structural member. Using this approach, students learn to delineate related and unrelated causalities, and determine the most probable failure scenarios. By contrast to traditional forensic failure studies that use case histories, this approach represents a true scientific forward analysis and allows students to practice logical inductive reasoning, instead of the more deductive approach that is traditionally applied to forensic investigations.

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