Applications of engineering mechanics in forensic engineering

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Abstract The inclusion of examples from engineering practice in the classroom is a key to generating student interest and motivation. Ideal examples allow students to apply both concepts from course material and creative problem-solving methodology to a 'real world' problem. While open-ended design problems are often used as case studies in upper-level engineering courses, students in the early phases of their academic career often lack the background necessary to handle even simple design case studies with proficiency. Therefore, the practical use of design case studies is extremely limited in first two years of an engineering curriculum, and is limited to trivial exercises or closed-ended parametric optimization problems. As an alternative, case studies involving the investigation and reconstruction of accidents involving engineering systems can be employed. Such case studies allow the students to demonstrate their engineering problem-solving skills, requiring the students to propose a likely accident scenario and prove their scenario using engineering analysis and the formal scientific method. In this paper, the use of forensic engineering case studies in an introductory mechanics course sequence is outlined. Three case studies involving the use of statics, dynamics, and mechanics of materials are presented.

Keywords engineering mechanics; forensic engineering

Introduction

The incorporation of practical examples from engineering practice into the classroom is a constant challenge for engineering faculty members. From their introductory courses, students crave 'real world' applications to motivate their engineering studies. With the emphasis placed on the incorporation of concepts of open-ended design in the engineering curriculum, design projects are often used to serve this motivational function [1, 2]. Even in introductory courses in engineering science, textbook authors are now including design problems aimed at freshman and sophomore students [3].

While no one disputes the value of including practical applications in introductory engineering course work, the tendency to rely on design projects as the lone source of such applications can be challenged. The difficulties in relying on design applications early in the curriculum have been discussed by previous authors [2]. Typical difficulties include:

- The limited abilities and experiences with engineering topics and the design process often reduce such early efforts in design to a trivial level.
- Simple design studies geared to introductory courses generally are limited to parametric optimization problems, and do not allow the students to exercise creative problem-solving skills. This especially true in introductory mechanics

courses, where a typical 'design' problem might involve simply selecting dimensions for a predesigned truss structure or mechanical component.

Therefore, while design projects may be ideal for motivating upper-division engineering students, there is a need for practical case studies that can be used to motivate students in introductory engineering courses, but that are more appropriate to the intellectual and experiential level of these students. The use of case studies from the field of forensic engineering is proposed in this paper.

Forensic engineering is defined as 'the application of the engineering sciences to the investigation of failures or other performance problems' [4]. It is a field of engineering that cuts across all disciplines, and required excellent technical and communication skills. Since it involves the direct application of concepts from engineering science, it offers ideal practical applications for incorporation into engineering science courses, even at the introductory level. Case studies from the field of forensic engineering take the form of a hypothetical 'accident scene'; students use the information provided to formulate a likely hypothesis as to how the accident occurred, and then use techniques from engineering science to prove or disprove their hypothesis. Forensic engineering case studies are well suited to inclusion in the classroom for the following reasons:

- They involve the direct application of concepts from engineering science to a real physical application.
- They allow the students to apply the scientific method, formulating a likely accident scenario (hypothesis) and then using scientific and mathematical techniques to prove or disprove their hypothesis.
- Problems are 'open-ended' in that multiple hypotheses may be considered, but they do not require the application of design methodology more appropriate to upper-division courses.

As secondary advantages, such case studies also introduce students to concepts from safety engineering early in the curriculum, and introduce students to a non-traditional but growing field of engineering practice.

A series of forensic engineering case studies has been formulated. These case studies are presented in the next three sections. They have been developed for used in an introductory course sequence in engineering mechanics, including the first courses in statics, dynamics, and mechanics of materials. One case study suitable to each course has been presented. These case studies are based both on those reviewed in existing literature [5, 6] and from the author's practice in forensic engineering. Conclusions based on the use of forensic engineering case studies in an engineering mechanics course sequence are presented in the final section.

Analysis of a ladder accident – forensic engineering application of engineering statics

The case study

The following information is provided to the students:

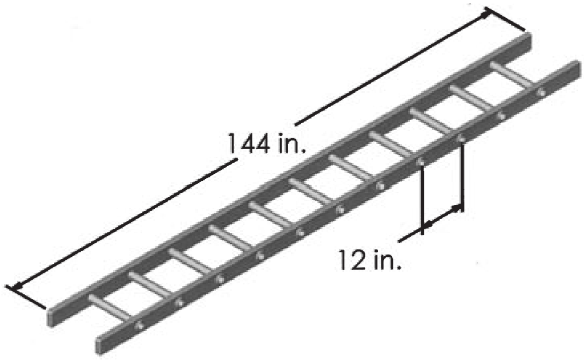

Fig. 2.1 *Ladder.*

Description of the accident

A person 5′11″ tall and weighing 210 lb was injured in a fall from a ladder. A witness at the scene indicates that the man had climbed about two-thirds of the way up the ladder when both he and the ladder fell to the ground. The climber sustained a broken left arm, and has no memory of the details of the accident.

Description of the accident scene

The Ladder: The ladder is 12-foot long and constructed of aluminium. A picture of the ladder is shown in Fig. 2.1. The ladder appears to be in good structural condition. Examination of the required warning labels affixed to the ladder yields the following information:

- The ladder is classified as a 'Type II' ladder, meaning it has a maximum load capacity of 225 pounds.
- The maximum standing height is 9′2″.
- The ladder is to be erected at 75° from horizontal.
- The ladder is to be erected on dry, level ground.
- The ladder should be erected such that no less than two feet and no more than three feet of the ladder extends above the roofline.
- The ladder conducts electricity.

The Site: The ladder was erected against a flat-roofed building with an aluminum rain gutter, shown in Fig. 2.2. The witness indicates that approximately 3 feet of the ladder extended above the roofline. The ground beneath the ladder was a cobblestone surface. The day of the accident was overcast (no precipitation) and 45°F.

Tasks at hand

As the forensic engineer called on to investigate, please complete the following tasks:

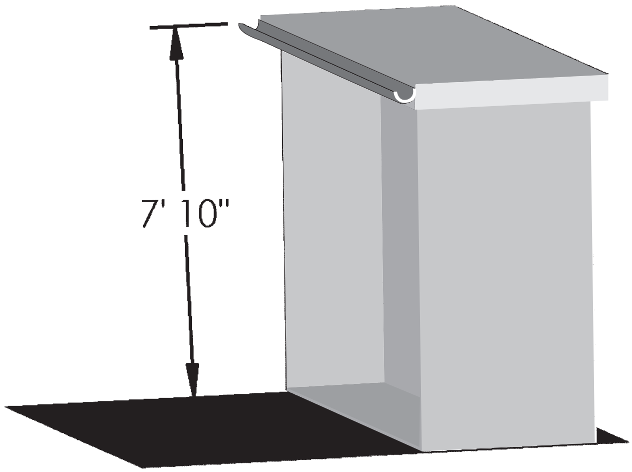

Fig. 2.2 *Accident Scene.*

- Develop a simple mathematical model of the system, using principles of statics. State all assumptions.
- Formulate a hypothesis as to how the accident occurred.
- Using the mathematical model you have developed, either prove or disprove your hypothesis.
- Draw conclusions about the *likely accident scenario*

The solution

The model

A simplified analysis of the classic 'ladder slipout' problem can be derived from the free body diagram shown in Fig. 2.3. Since the support at the roofline is metal-on-metal (a low friction condition) and the typical angle of a ladder is such that the reaction at the top support is small, friction at the upper support has been neglected. Applying the principles of static equilibrium, the following equations apply:

$$R_x = R_u \sin\theta \tag{2.1}$$

$$N - W + R_u \cos\theta = 0 \tag{2.2}$$

$$Wx \cos\theta = R_u L \tag{2.3}$$

The key to avoiding ladder slipout is that the required horizontal force R_x at the ladder/ground interface must not exceed the maximum static friction force (μN); if it does, the ladder is not in static equilibrium, and slipout occurs.

The likely accident scenario hypothesis

The most likely cause of the accident is that the ladder slipped at the ladder/ground interface, causing the ladder and climber to fall to the ground.

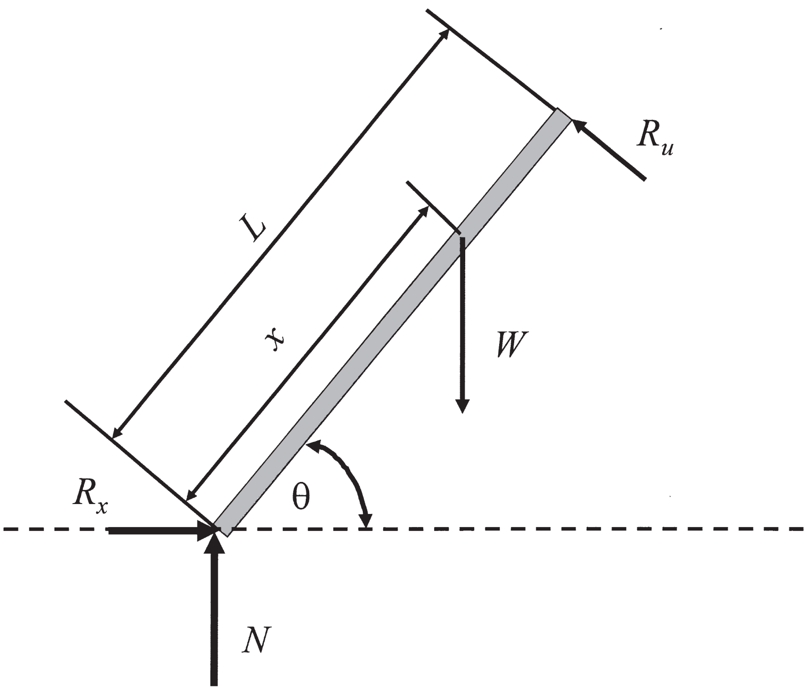

Fig. 2.3 *Free Body Diagram of Ladder.*

Test of the hypothesis

Using the sketch of the accident scene as a guide, the following values in equations 2.1–2.3 were determined:

- $L = 9$ ft.
- $x = 6$ ft.
- $\theta = 60°$

Solving equations 2.1–2.3 with these values yields the following results:

- $R_u = 70$ lb.
- $R_x = 60.6$ lb.
- $N = 175$ lb.

With these results, ladder slipout would have occurred if the coefficient of friction μ at the ladder/ground interface was less than 0.35 at the time of the accident. While the exact conditions at the time of the accident cannot be recreated, published values [3] indicate that the coefficient of friction for metal on stone is generally in the range of 0.30 to 0.70. Therefore, the coefficient of friction that would have had to exist at the ladder/ground interface at the time of the accident for ladder slipout to have occurred is consistent with published values. The fact that the accident occurred on a cold morning suggests that perhaps condensation may have occurred on the cobblestone surface, indicating that a coefficient of friction on the low end of published values could be expected.

Accepting the premise that ladder slipout occurred, the next step is to determine what caused the conditions that led up to the accident. A check of the likely ladder setup indicates that the 60° angle of setup is less than the 75° setup angle recommended for the ladder. Assuming that the coefficient of friction computed in the ladder slipout case existed, equations 2.1–2.3 are solved with the following setup parameters:

- $L = 8.1$ ft.
- $x = 8.1$ ft. (a worst-case scenario, where the climber is at the top support)
- $\theta = 75°$

The results are as follows:

- $R_u = 54.4$ lb.
- $R_x = 52.5$ lb.
- $N = 196.0$ lb.

With the assumed value $\mu = 0.35$, the maximum friction force at the ladder/ground interface is 68.6 pounds, sufficient to prevent ladder slipout even when the climber is standing near the upper support. This indicates that even with the low coefficient of friction that was likely present at the time of the accident, the ladder would not have slipped out if the recommended setup angle had been used. Therefore, it is likely that an improper setup of the ladder resulted in the conditions that caused the accident.

Conclusion: The likely scenario is that an improper setup of the ladder at a 60° angle resulted in a friction force at the ladder/ground interface insufficient to hold the ladder in place, and led to a ladder slipout accident.

Analysis of a traffic accident – forensic engineering application of engineering dynamics

The case study

The following information is provided to the students:

Description of the accident

A small two-door economy car and a large four-door sedan were involved in a traffic accident. The economy car was traveling east through an intersection on a road with a stop sign at the intersection. The sedan was traveling north through the same intersection on a road with no traffic control device. The cars collided in the intersection, and came to rest in a parking lot on the northeast corner of the intersection. No witnesses are available.

Description of the accident scene

The Intersection: A dimensioned sketch of the accident scene is shown in Fig. 3.1. The

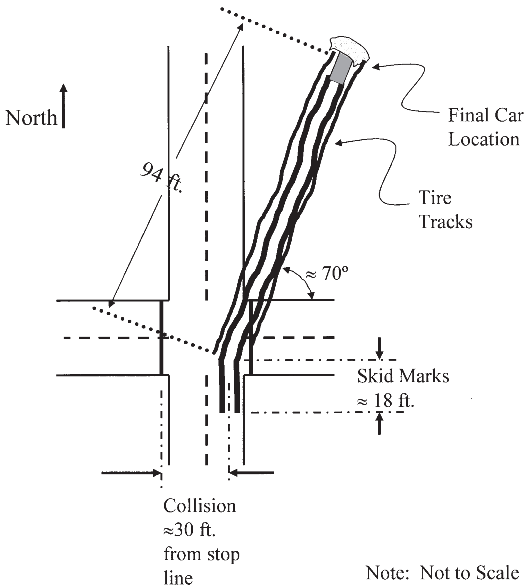

Fig. 3.1 *Sketch of Automobile Accident Scene.*

eastbound lane, in which the economy car was traveling, is controlled by a stop sign. The northbound lane, in which the sedan was traveling, was not controlled. The speed limit in both directions is 35 mph. The road surface is asphalt, and was in good condition. Weather conditions on the night of the accident were dry and 66°F.

The Vehicles: Both vehicles were less than one year old. The economy car weighs 2500 pounds, and the sedan weighs 3500 pounds. The economy car was a front-wheel drive vehicle, and the sedan was a rear-wheel drive vehicle.

Tasks at hand

As the forensic engineer called on to investigate, please complete the following tasks:

- Develop a simple mathematical model of the system, using principles of dynamics. State all assumptions.
- Formulate a hypothesis as to how the accident occurred.
- Using the mathematical model you have developed, either prove or disprove your hypothesis.
- Draw conclusions about the *likely accident scenario*.

The solution

The model

The speed of the vehicles at the time of the collision is a useful piece of information when reconstructing a traffic accident. The first step in this process is the construction of a mathematical model of the collision. The collision will be modeled using principles of work and energy. It will be assumed from the condition of the vehicles after the accident that they traveled together from the point of impact to their final resting spot on the lawn. It will also be assumed that neither vehicle was being propelled from the point of the collision to the point where the vehicles came to rest in the parking lot; during this period, the only relevant external force acting of the vehicles was friction at the tire/ground interface. Under this information, a model can be used to determine the speed of the two vehicles immediately after the collision by assuming that the two vehicles lock together upon impact and that their total kinetic energy at the instant of impact is dissipated by sliding friction as they come to rest:

$$\frac{1}{2}\frac{(w_1 + w_2)}{g}v^2 = (w_1 + w_2)\mu d \tag{3.1}$$

where w_1 and w_2 are the vehicle weights, g is gravitational acceleration, v is the speed of the two cars as they move together immediately following the collision, μ is the coefficient of friction at the tire/ground interface, and d is the distance traveled from the point of the collision to the stopping point.

Using the speed obtained from equation 3.1 and the angle of the skid measured from Fig. 3.1, the velocity vector of the two-car system immediately following the collision can be obtained as follows:

$$\vec{v} = v\cos\theta\vec{i} + v\sin\theta\vec{j} \tag{3.2}$$

where the $\vec{i}$ unit vector that points east and the $\vec{j}$ unit vector that points north.

Using this velocity vector, the principle of conservation of momentum can be applied to determine the individual speed of each vehicle immediately prior to the collision:

$$\frac{w_1}{g}v_1\vec{i} + \frac{w_2}{g}v_2\vec{j} = \frac{w_1 + w_2}{g}\vec{v} \tag{3.3}$$

where v_1 and v_2 are the speeds of the economy car and the sedan, respectively.

It may also be of value to determine the speed of the individual vehicles at some point before the collision. If it can be determined that the brakes of the vehicle were locked at some distance D from the collision point, the speed of the vehicle immediately prior to the locking of the brakes can be determined using a form of the velocity/acceleration relationship under the assumption of constant deceleration:

$$v_{o_i} = \sqrt{v_i^2 + 2\mu gD} \tag{3.4}$$

where v_{o_i} is the speed of vehicle i immediately prior to braking.

The likely accident scenario hypothesis

Because the eastbound economy car was entering the intersection from a lane with a stop sign, it is hypothesized that the economy car failed to obey the traffic control device and entered the intersection, where it was hit by the northbound sedan.

Test of the hypothesis
Analysis of Fig. 3.1, information about the vehicles, and library research yields the following values for use in equation 3.1:

- $w_1 = 2500$ lb.
- $w_2 = 3500$ lb.
- $\mu = 0.71$ for rubber on asphalt [see reference 7]
- $g = 32.2$ ft/s^2
- $d = 94$ ft.

Based on these values, the speed of the two vehicles just after the collision is found to be $v = 65.6$ ft/s. Using this value, and measuring the angle of the post-collision skid marks to be approximately 70° (see Fig. 3.1), the velocity vector associated with the two cars immediately following the collision is found to be:

$$\vec{v} = (22.4\,ft/s)\vec{i} + (61.6\,ft/s)\vec{j}$$

Applying equation 3.3 yields that the eastbound economy car was traveling at a speed of $v_1 = 53.8$ ft/s, or 36.7 mph. There are two basic possible driver actions to be considered for the economy car:

1 The driver could have stopped at the stop sign, accelerated into the intersection, and been hit by the northbound sedan.
2 The driver could have failed to stop at the stop sign, and proceeded into the intersection without stopping.

Considering driver action #1, it would have been necessary for the driver to accelerate from a stop to 36.7 mph in the distance between the stop sign and the collision. Using a form of the velocity/acceleration relationship:

$$v^2 = v_o^2 + 2a(x - x_o) \qquad (3.5)$$

and noting that the collision occurred only 30 feet from the stop sign, this would imply a constant acceleration of 48.2 ft/s^2 over the 30 foot interval; using $F = ma$, this would imply a total propulsive force of 3742 pounds at the tire/ground interface. Using the conservative assumption that the entire weight of the vehicle is carried by the two drive wheels, the maximum propulsive force that can be generated by the friction at the interface is:

$$\mu w_1 = 1,775 \text{ pounds}$$

before tire slippage would occur. This apparently rules out the possibility that the eastbound vehicle accelerated from a full stop at the stop sign; this fact, and the lack of any pre-collision tire marks at the scene, indicates that it is more likely that the driver failed to obey the traffic control device.

For a full reconstruction of the accident, however, it is prudent to consider the actions of the driver of the sedan as well. Again applying equation 3.3, the speed of the sedan immediately prior to the collision can be computed as $v_2 = 105.6$ ft/s, or 72.0 mph. Noting the 18 feet of skid marks in the northbound lane prior to the collision point, and applying equation 3.4, indicates that the sedan was traveling at a speed of approximately 75 mph when braking began. This is well in excess of the posted 35 mph speed limit for the intersection.

Conclusion: The most likely accident scenario is that the eastbound vehicle failed to comply with a traffic control device, and proceeded into the intersection at a speed consistent with the posted speed limit. It was struck by the northbound sedan, which was traveling at a speed of 75 mph as it approached the intersection, a rate that is more than 40 mph above the posted limit. While the failure by the eastbound driver to comply with the traffic device is a primary cause of the accident, a secondary cause (and one that exacerbated the severity of the accident) was that the northbound driver was traveling at an improper speed.

Analysis of a structural failure – forensic engineering application of mechanics of materials

The case study[1]

The following information is provided to the students:

Description of the accident

A large automotive convention was taking place at a newly-opened convention hall. A keynote address was scheduled, where two new 'concept cars' would be unveiled. As the keynote address began, one of the new cars was slowly driven onto each of two suspended walkways located over the convention floor. As the cars reached the center of the walkways, the walkways suddenly collapsed, results in numerous serious injuries and deaths on the convention floor below. All of the witnesses to the accident report that the collapse initiated on the side of the walkways where a suspension rod was located.

Description of the accident scene

The Structure: A schematic of the walkways is shown in Fig. 4.1. Each walkway is simply supported on one end, and suspended from above by a suspension rod on the other end. The structural dead load of each walkway is 6200 pounds, and each was designed to carry an additional 4000 pounds of capacity ('live load'), which was clearly indicated by a plaque on the structure.

Other Information: Convention organizers indicate that the weight of the 'concept cars' was approximately 3500 pounds each, with each driver weighing approximately 200 pounds, placing the total structural load 300 pounds under the maximum. In addition, the structural engineer of record has indicated that a factor of safety of 1.5 was used in sizing all structural components used in the walkway with respect to the stated design load limits.

[1] This case study is an abstraction of the 1981 Hyatt Regency walkway collapse, detailed in numerous popular engineering works. One good treatment is that of Petroski (Ref. 5). Many details have been changed for this case study.

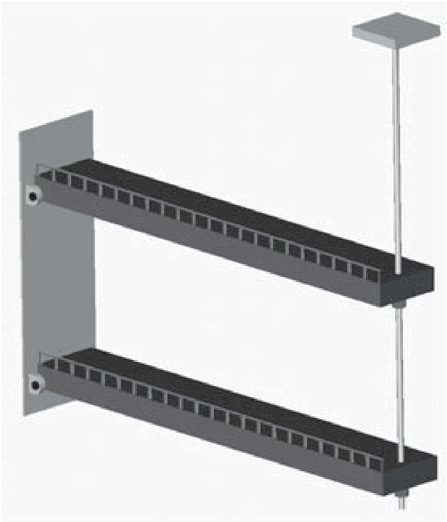

Fig. 4.1 *Sketch of the Walkway.*

The structural engineer of record has examined the remains of the structure, and has noted a minor deviation in the way the structure was constructed versus the way it was designed. The difference is in the connection detail where the suspension rods interface with the structure; the difference is highlighted in Fig. 4.2.

Tasks at hand
As the forensic engineer called on to investigate, please complete the following tasks:

- Develop a simple mathematical model of the system, using principles of statics and mechanics of materials. State all assumptions.
- Formulate a hypothesis as to how the accident occurred.
- Using the mathematical model you have developed, either prove or disprove your hypothesis.
- Draw conclusions about the *likely accident scenario*

The model
Since there is evidence that the collapse initiated in the neighborhood of the suspension rods, and since there is evidence of a deviation from the original design in this area, structural modeling will be performed to determine the loading conditions in this area. Two models will be developed; one for the 'as designed' case, and one for the 'as built' case.

The 'As Designed' Model: A free body diagram showing the 'as designed' case is shown in Fig. 4.3. Using the assumption that the entire combined weight of the struc-

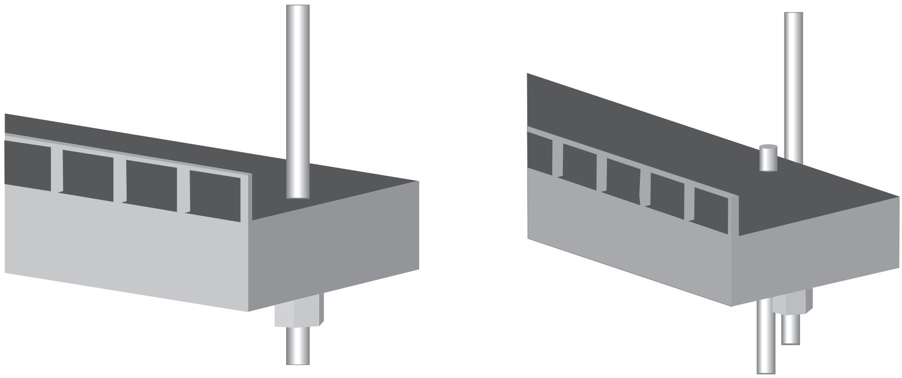

Fig. 4.2 *Construction Details.*

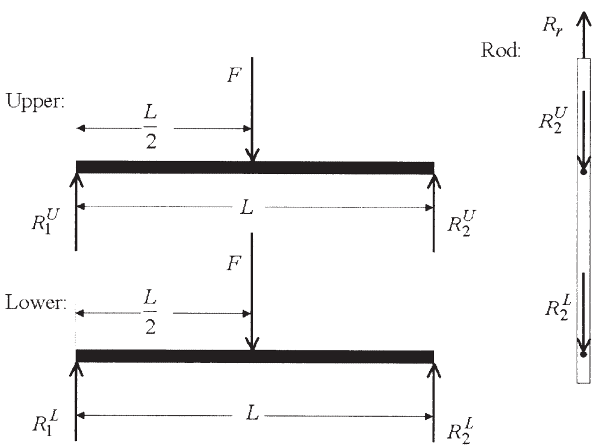

Fig. 4.3 *Free Body Diagram of 'As Designed' Walkway.*

ture and the weight of the car/driver act at the midpoint of the structure, equilibrium analysis can be performed on the structure. Applying static equilibrium, the reactions can computed:

$$R_1^L = R_2^L = \frac{F}{2} \tag{4.1}$$

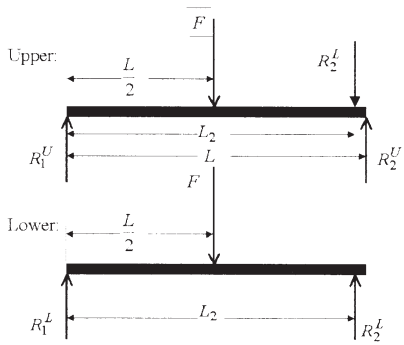

Fig. 4.4 *Free Body Diagram of 'As Built' Walkway.*

Performing identical analysis on the upper walkway yields identical results:

$$R_1^U = R_2^U = \frac{F}{2} \tag{4.2}$$

Applying these results to the free body diagram of the rod yields the result $R_r = F$.

The 'As Built' Case: A free body diagram showing the 'as built' case is shown in Fig. 4.4. Using the assumption that the entire combined weight of the structure and the weight of the car/driver act at the midpoint of the structure, and invoking the approximation that $L_2 \approx L$, equilibrium analysis can be performed on the structure. Analyzing the lower walkway yields the following result:

$$R_2^L \approx \frac{F}{2} \tag{4.3}$$

$$R_1^L \approx \frac{F}{2} \tag{4.4}$$

Performing analysis on the upper walkway yields these results:

$$R_2^U = F \tag{4.5}$$

$$R_1^U \approx \frac{F}{2} \tag{4.6}$$

The likely accident scenario hypothesis

It is hypothesized that a field change in the suspension rod system that deviated from the structural design caused a dramatic change in the structural loading condition, resulting in a structural failure of the walkways.

Test of the hypothesis
Examination of equations 4.1–4.6 indicates that the reaction forces modeled by these equations are virtually identical in the 'as designed' and 'as built' cases. The major difference in the loading condition between the two cases is shown by comparison of equations 4.2 and 4.5. In the 'as designed' case, the reaction force $R_2^U \approx \frac{F}{2}$, indicating the structural components providing this reaction force are required to carry half of the combined design dead/live load. In this design, the value for R_2^U is determined to be 5100 pounds. The reaction force is provided by a nut supported by a threaded rod, as shown in Fig. 4.2. Based on the assertion of the structural engineer, a factor of safety of 1.5 was employed; therefore, it can be inferred that the nut/thread system was sized to carry 7650 pounds. Any load in excess of this would result in the stripping of the threads that support the load, causing the nut to strip off the threaded rod.

Examining the 'as built' case, equation 4.5 indicates that under the implementation of the field change, the reaction force $R_2^U = F$. This is twice the reaction that resulted in the 'as designed case' when fully loaded. When the car was driven onto the walkway, the total load F seen by the structure was 9900 pounds; the nut/thread connection that supported the upper walkway would have seen this entire load. However, it has been shown that the nut/thread system was only designed for a loading of 7650 pounds. The loading conditions resulted in the stripping of the threads that hold the nut on the threaded rod; the nut tore loose from the rod, and the upper walkway collapsed.

Conclusion: A field change in the construction of the walkway resulted in a loading condition not foreseen in the design of the structure. This unforeseen loading condition exceeded the structural capacity of a fastener supporting the walkway, leading to a structural failure of the connection and the collapse of the structure.

Conclusions

The use of forensic engineering case studies in introductory mechanics courses has proven to be an effective means to motivate student interest and bring 'real world' applications into the classroom. These case studies require extensive analytical skills and quantitative reasoning abilities, but do not require the extensive use of design processes and tools required for design-based case studies. Students are motivated by the opportunity to apply their newly-acquired analytical skills to real engineering systems, and enjoy the opportunity to perform engineering 'detective work'.

These case studies can be implemented either as in-class projects or as homework assignments with in-class follow-up discussion. In addition to providing the students an opportunity to exercise their analytic skills, these case studies also provide a springboard to class discussion on numerous engineering topics, such as:

- *Uncertainty Analysis:* How much uncertainty is inherent in your analysis? Can the uncertainty be quantified? What is 'reasonable engineering certainty'?

- *Experimentation:* How would you further test your hypothesis with experimentation? What type of experiment would you design? What type of data would you collect?
- *Design for Safety:* Could you redesign the systems examined in the case study to minimize the chance of the accident occurring? What effects would your design change have on the overall functionality and cost of the system?
- *Engineering Ethics:* If you were an employee of the corporation that had designed the system examined in the case study, what actions would you take? What are your ethical responsibilities as an engineer? As a forensic engineer employed by a law firm for a liability case, what ethical dilemmas might you face?
- *Communication Skills:* How would you convey your conclusions to someone not familiar with engineering terminology?

The case studies presented in this paper are typical, but not exhaustive; with numerous books and publications dealing with engineering accidents and failures available [5, 8], additional forensic engineering case studies can be developed.

References

[1] S. D. Sheppard, 'Design as cornerstone and capstone', *Mechanical Engineering: Design Supplement*, November 1999.
[2] K. N. Otto and Kristen L. Wood, 'Designing the design course sequence', *Mechanical Engineering: Design Supplement*, November 1999.
[3] F. P. Beer and E. Russell Johnston Jr., *Vector Mechanics for Engineers: Statics* (*6th Edition*), McGraw Hill, St. Louis, 1996.
[4] *National Academy of Forensic Engineers* website, http://www.nafe.org, updated 9/26/00.
[5] H. Petroski, *To Engineer Is Human: The Role of Failure in Successful Design*, Vintage Books/Random House, New York, 1992.
[6] L. B. Fricke, *Traffic Accident Reconstruction*, Northwestern University Traffic Institute, Evanston, IL, 1990.
[7] E. A. Avallone and Theodore Baumeister (editors), *Marks' Standard Handbook for Mechanical Engineers* (*9th Edition*), McGraw-Hill, St. Louis, 1978.
[8] J. R. Chiles, *Inviting Disaster: Lessons from the Edge of Technology*, Harper Business, 2001.