CAUSES, PREDICTION AND PREVENTION OF STRUCTURAL FAILURES: A STATE-OF-THE-ART REPORT

Rahmat A. Shoureshi, Amir H. Chaghajerdi, and Susan J. McCaffery
Colorado School of Mines, Golden, CO 80401
Rshoures@mines.edu, achaghaj@mines.edu, and smccaffe@mines.edu

Abstract

The phenomenon of structural failure is widespread, potentially devastating, and year by year continues to give rise to billions of dollars worth of damage expenses. Although there are already exists a vast quantity of documentation in the literature regarding structural failures, much work still needs to be done on creating new models and developing novel technologies to help prevent, or at least reduce the effects of, structural failures in the years ahead. Hence the purpose of this paper is to highlight a number of the currently available predictive models and preventative technologies, and indicate some future directions that may be expected in the field of structural failure research.

Introduction

Structural failures are sadly a numerously recurring, worldwide problem. The number of documented cases is vast and many of these instances have led to devastating consequences, such as loss of life and large-scale physical destruction which amounts to billions of dollars worth of damage yearly. Since everyone is a potential victim of structural failure, this phenomenon has for some time received widespread attention, not only in the form of academic journal papers, but also through discussions at conferences, reports in the media, and even congressional hearings. However, much research on predictive models and preventative technologies for structural failures still remains to be done. The purpose of this paper is to initially summarize the possible causes, both natural and man-made, and consequences of structural failures. Secondly, a number of methods for predicting structural failures that are available in the literature are described, and feasible methods for structural failure prevention, primarily in terms of sensor technologies, are then considered. Finally, before the concluding remarks are made, a discussion is provided on what the future may hold with regards to structural failures.

Causes and Consequences of Structural Failures: Natural and Man-made

There exist a number of different natural causes of structural failures, namely earthquakes, volcanoes, hurricanes, tornadoes, high winds, flash floods and floods, landslides, thunderstorms and lightning, hail, winter storms, fire, erosion, land subsidence, and corrosion. Much information on these topics is available on the web: an example of a comprehensive source is the web-site of the United States Geological Survey (USGS) (1998), who point out that natural hazards alone cost the United States an average of fifty billion dollars per year. Typical examples of man-made causes are firstly those phenomena which can also be linked to natural structural failures, *i.e.*, landslides, fire, erosion, land subsidence, and corrosion, and secondly those which are purely man-made, *i.e.*, overloading, neglect, explosions, design and construction errors, and ethics. A summary of the damage caused by man-made disasters on a number of different types of structure is given by Eldukair and Ayyub (1991), who report that the total cost of structural damage between 1975 and 1986 due to man-made causes, just for the structures used in their study, was three and a half billion dollars.

Methods of Predicting Structural Failures

Modeling for structural failure prediction can be considered to be the first step in developing an effective hazard mitigation strategy. Examples of such models are divided to analytical, numerical, constitutive, and deterministic. An interesting paper by Bruneau (1994) reviews a number of primarily advanced analytical models for the seismic evaluation of unreinforced masonry buildings. Bruneau (1994) explains that the need for models of such seismic evaluation arose from the fact that many old masonry buildings were designed with little or no consideration for seismic effects.

A popular class of methods for damage evaluation of a structure is the set of non-destructive techniques, and in particular modal analysis. Topole (1995) describes an analytical model of non-destructive damage evaluation which predicts the locational severity of structural damage by using modal characteristics of the damaged structure. Another paper on modal analysis is that by Chang *et al.* (1995) for bridge damage detection, and more detail on the theory behind modal analysis can be found in the book edited by Bray and McBride (1992).

Bruneau (1994) also discusses finite-element models for seismic evaluation of unreinforced masonry buildings. He explains that linear elastic finite-element analyses have been used to establish the state of stress in unreinforced masonry structures and can be useful in providing guidance as to the governing failure model, ultimate elastic capacity, natural frequencies, mode shapes, and modal participation factors of uncracked, unreinforced masonry buildings. However, such models provide limited insight into the ultimate strength and seismic behavior of the structures and produce unavoidable local stress concentrations that require careful interpretation. As a result, modifications to the linear elastic finite-element models have been composed by a number of researchers, and these are also discussed by Bruneau (1994).

Finite elements were in addition exploited by Baskaran and Stathopoulos (1994) to predict the effects of wind on structures. They also provide a state-of-the-art review on other computational wind engineering techniques, including finite-difference and control-volume methods. Another paper concerning the use of computational software to model wind, as well as seismic, factors is that by Hays (1991), which concerns the design of a high-rise industrial tower in India.

Examples of constitutive models for structural failure are presented in Bhattacharjee and Leger (1992). These models are concrete constitutive models and they enable non-linear seismic analysis of gravity dams. They point out that the need for constitutive models arose from the lack of consistent results from, and virtually impossible verification of, previous models for finite-element crack propagation analysis of concrete structures.

A deterministic model is employed by, for example, Powell and Allahabadi (1988) to predict damage caused by earthquakes. They consider two types of techniques, the first of which is based on the balance between some demand on the structure and its corresponding capacity, and the second on the degradation of some structural property. For each technique, alternative choices of the damage parameters are computed and suggestions for the relation of the damage parameters to damage indices are suggested.

Prevention of Structural Failure: Sensor Technology

As mentioned before, models for structural failure prediction are a first step in hazard mitigation. However, at the heart of hazard mitigation today is sensor technology. Sensor technology, for the case of civil infrastructures, includes devices such as accelerometers, acoustic transducers, strain gauges, and optical fibers. A special kind of sensor known as a “smart” sensor is also considered.

Accelerometers are used in the sensing and measurement of vibration. Essentially, an accelerometer measures the force required to accelerate a mass contained within the device. These devices are commonly used in conjunction with the non-destructive evaluation technique of vibration analysis, an example of which is described by Lauzon and DeWolf (1995) in conjunction with bridges. As explained in Bray and McBride (1992), accelerometers are good, rugged sensors, but their frequency range is limited which precludes their use from many types of testing.

Acoustic transducers including piezoelectric transducers, air-gap capacitive transducers, and magnetostriction transducers are considered as acoustic transducers are listed in Bray and McBride (1992). In addition, a new kind of acoustic transducer is the electromagnetic acoustic transducer (EMAT): this has recently been successfully employed by Chenoweth (1998) in the health assessment of substation ground mat risers.

Piezoelectric transducers have been the main kind of acoustic transducers employed in practical, field-type monitoring of structural components or devices in recent years. These transducers are very sensitive, reliable, and suitable for the monitoring of a wide range of frequencies. Their primary disadvantage is that they have a limited bandwidth and do not accurately reproduce the original amplitudes outside of their response range. Details of the wide variety of sensing elements of piezoelectric transducers are given in Bray and McBride (1992). Two examples of the application of piezoelectric transducers in non-destructive acoustic emission testing are described by Landis and Shah (1995) and Sami *et al.* (1995). They use the transducers to help monitor crack growth and deduce microfracture mechanisms in quasi-brittle materials, whilst Sami *et al.* (1995) employ piezoelectric transducers in the performance evaluation of composite rods employed as reinforcing bars in concrete structures.

Air-gap capacitive transducers monitor surface displacements via changes in capacitance between a probe and the surface of the transducer. These transducers are best suited to signal analysis tasks, relating signal frequencies and wave shapes to specific mechanisms that generate emissions, because their frequency response is comparatively flat and they are also easily calibrated. Magnetostriction transducers are more mechanically rugged than piezoelectric transducers. They maintain their transduction characteristics at high temperatures and in the presence of nuclear radiation. Thus they are primarily suitable for remote sensing through waveguides in hostile environments. However, since the frequency of a transducer is inversely proportional to its dimension in the vibration direction, their high-frequency response is limited by geometry. The frequency response of magnetostriciton transducers is generally no higher than one mega hertz.

Two types of strain gauges, *i.e.*, electrical resistance and acoustic strain gauges, are considered following. Other kinds of strain gauges are described in the book edited by Window and Holister (1982).The most powerful tool in the field of experimental stress analysis since 1940 has been the bonded electrical resistance strain gauge. This gauge is one of the most accurate, sensitive, versatile and easy-to-use sensors available, as well as being relatively low cost, linear in output, and easily installable. Excellent performance characteristics, particularly in stability, temperature compensation, and creep, have resulted from years of commercial development and industrial and research investigations. In turn, the electrical resistance strain gauge has become the basic sensing element of very high precision load transducers and weighting sensors. This type of strain gauge is described in great detail in Window and Holister (1982).

A recent development in strain gauges is the acoustic strain gauge. This is described in an article in Civil Engineering (1997) and has two major advantages. They are less time consuming to install and also can be installed and uninstalled as necessary. With the permanent attachment of conventional strain gauges, constant adjustment and repair is necessary as their performance becomes affected by such external factors as weather, moisture and salt build-up.

Fiber-optic technology is a revolutionary branch of optics which was largely driven by the telecommunication industry in the 70s and 80s, in combination with mass commercial production of low-cost, opto-electronic components. In current times, the product outgrowths of fiber-optic telecommunications is being combined with opto-electronic devices to create fiber-optic sensors. Application areas for fiber-optic sensors are vast, and these sensors have the potential of replacing most of today's existing environmental sensors. The advantages of fiber-optic sensors are listed in the book edited by Udd (1991). Fiber-optic sensors are small in size, light in weight, and are immune to electromagnetic interference. Environmental ruggedness allows fiber-optic sensors to be used in high-temperature operations and to be capable of withstanding extreme vibration and shock levels. Furthermore, fiber-optic sensors have high sensitivity and large bandwidths.

Literature on fiber-optic sensors is limitless: a handful of examples is given below. Murphy and Jones (1993) report on the usage of a retrofit optical fiber strain gauge and diaphragm in a commercially available pressure measurement system. Zumberger *et al.* (1988) describe laboratory experiments on single-mode optical fibers for use in measuring earth strain. Danigel (1995) documents the development of a fiber-optic photometer system for the performance of a wide variety of on-line measurements in chemical plants. Furthermore, review papers are provided by Ning *et al.* (1995) on fiber-optic current-sensing techniques and by Berthold III (1995) on microbend fiber-optic sensors.

Smart sensors are a new development that is revolutionizing integrated circuit (IC) manufacturing: it is the advanced software which capitalizes on recent advances in sensor technology that makes the sensors "smart". Such smart sensors are one part of "smart structure technology". As described by Measures (1997), smart structure technology is bringing together many diverse fields, for example microelectronics, fiber-optic sensors, integrated optics, control actuators, artificial intelligence, and structural engineering.

Measures (1997) also reports on the development of embedded optical fibers: in his case, these embedded fibers were found not to reduce the strength or damage resistance of composites and to be capable of detecting load-induced growth of damage. The embedding of optical fibers to produce smart structures is becoming more and more widespread, and much literature is now available on the subject. A review paper by Rogers (1986) highlights the important feature of optical fibers of being able to offer unique advantages for spatially-distributed measurements, and Lerner (1997) states that "one of the great advantages of fiberoptic sensors is that they can act as distributed sensors, recording a parameter over the entire length of the fiber". Examples of applications of embedded sensors are those described by Fuhr *et al.* (1993), Lesko *et al.* (1992), Masri *et al.* (1994), and Pierce *et al.* (1996). Embedding of fibers is not the only means to make a structure smart: for instance, Rizkalla and Tadros (1994) document details of a highway bridge in Calgary, Canada which includes pretensioned carbon-fiber-reinforced-plastic (CFRP) tendons. In addition, Chung (1998) describes "multifunctional concretes", which exhibit good load-bearing ability, as well as one or more other structural damage prevention properties.

Before closing this section, it is worth mentioning some interesting references on active systems, such as papers by Bell (1997) on the structural vibration control of cable-stayed bridges, by Cox (1992) on active vibration control, by Fogg *et al.* (1992) on active structural acoustic control, by Shoureshi and Bell (1995) on control issues related to active vibration attenuation, and by Shoureshi *et al.* (1995) on active control systems.

The Future of Structural Failures

As indicated by Housner *et al.* (1997a), although much progress has already been made in structural control, there still remain many topics related to the control and monitoring of structural failures which require further study and analysis. The current status of the field of structural failure prevention would appear to point to smart and intelligent structural systems for future improvement of existing practices. In more detail, Housner *et al.* (1997b) recommend that future research should be directed towards the development of devices and algorithms for passive, active, semi-active, and hybrid control of non-linear systems, of modeling and identification of non-linear dispersed and infrastructure systems, of innovative, high performance and intelligent material systems, of health monitoring, condition assessment and damage detection of dispersed civil infrastructure systems, and of intelligent sensors for distributed sensing and control in dispersed systems. Both Housner *et al.* (1997a) and Housner *et al.* (1997b) suggest that future progress will be expedited by multi-national studies and collaborations, with the encouragement of data and technical information interchange.

Conclusions

This paper has indicated that the causes of structural failures are numerous and the consequences potentially devastating, particularly in terms of resulting damage costs. In an attempt to predict structural failures before they occur, a selection of models have been developed by various researchers. On the other hand, prevention of structural failure is the key issue, and many sensor technologies have been and are being employed to try to counteract the effects of external disturbances which may lead to structural failure. The most promising technology both in the present and in the future is that concerned with smart sensors. In short, the future aim should be to eliminate man-made disasters altogether and to be able to predict and at least reduce the impact of structural failures from natural causes before they occur.

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