BRIDGE FAILURE AND CONSEQUENCES

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Abstract: This paper presents a review of bridge failure and its direct; indirect consequences statistics, based on a literature survey and available information through websites, focusing on RCC; PSC; steel composite bridges. Failure cases have distinguished between those resulting in bridge total collapsed and partially collapsed, but resulted in the loss of serviceability. Classification of the most common failure causes and modes of failure is undertaken. The bridge failure results indicate that collapses due to natural hazards, design errors and limited knowledge are the most commonly encountered in bridges, followed by accidents and human error. When analyzed chronologically, the data demonstrate a decreasing trend for the collapses attributed to limited knowledge and an increasing trend in failures resulting from accidents and natural hazards. The findings obtained through the study of the failure of these bridges prove to be great values as these studies provide a big database to civil Engineer to enhance their knowledge to identify the causes of their failure. By Studying and evaluating the failure of these bridges, similar mistake can be avoided in the future by learning from the past. The trends revealed through statistical analysis can aid in identifying the potential of the most significant hazards affecting bridge structures and help in planning against their consequences. In terms of non-collapse cases, fatigue failures are found to be predominant in steel bridges. The paper concludes with a discussion of bridge failure consequences and their significance in risk assessment of bridge structures.

Keywords: Bridges, Failure, consequences, risk assessment

1. Introduction

Studying the failures of the past can be useful in mitigating the incidence and potential of future failures. Bridge failures are one of the most severe infrastructure problems facing the world today and usually cause significant economic losses and casualties. A first step towards the understanding and quantification of the risk of failure of bridges can be provided by acquiring knowledge on the failure mechanisms of existing structures and the root of the causes of the collapse. Identification may be done to get predominant failure causes and modes for each type of bridges to get the idea of failure and consequences pattern. Clearly, trends picked up through statistical analysis can aid in identifying and understanding the potential of the most significant hazards affecting bridge structures and help in planning against their consequences. Nevertheless, over the last decades, engineers have realized the importance of collecting and archiving information regarding structural failures and have attempted to review this information in a collective manner. Consideration of failure consequences is essential in structural design and assessment, as well as in the evaluation of the robustness of structural systems. Consequence classes are established for the purpose of reliability differentiation and the specification of recommended minimum values for the reliability index.

2. Bridge failure and consequences literature review

Failures of bridges have occurred ever since bridge building started thousands of years ago. A large part of the technical knowledge associated with bridge engineering today is based on the past failures of bridges. In the past century, bridge engineers learned substantially from studying historical failures of bridges. Each bridge failure has its unique features which makes it difficult to generalize the causes of failures for further application to other similar bridges. The more common causes and mechanisms of some bridge failures are reviewed. Responsible factors for failure are classified as natural factors (flood, scour, earthquake, landslide, wind, cyclone etc.) and human factors (improper design and construction method, collision, overloading, fire, corrosion, human error, lack of inspection and maintenance, etc.). Moreover, some of the bridge failures which have taken place in India over the last few decades are also discussed. Bridge collapse data are scarcely recorded in any developing countries. Wherever such data has been collected of this nature, may be used to determine the number of bridge collapses in the region annually. The causes of bridge collapses are numerically determined and associated with adverse effects of loss of life and average amount of traffic per day using the structure.

A database of bridge failure may be prepared and being used to compare consequence with the failure rate by cause. The failure rate by cause and consequence is evaluated qualitatively and quantitatively and can be utilized in future fault tree risk analysis and risk management decision making. This database of bridge failures is used to show the hazards bridges have failed from historically, determine the failure rate based on the cause of failure and formulated a conditional probability of failure accounting for the features under the structure. Consequences of bridge failures are established qualitatively by engineering judgment. Quantitative consequences are assessed from historical data available and compared with a benchmark set of guidelines for structural safety. A framework of qualitative consequences is constructed for a hierarchy of risk management decision making. Additionally, life loss parameters for fault tree risk assessment evaluating are established. The lack of comprehensiveness of the bridge failure database is evident in two forms; incomplete information on a failure and unrecorded failures. In order to better determine the bridge failure rate, most probable causes and modes of failure, in addition to mitigating failures in the design and maintenance processes, a more robust data collection system is required.

3. Causes of Bridge Failure

In an effort to identify the hazards that cause bridges to fail is shown in Table No- 1. Knowledge of potential hazards for bridges is an effective method to mitigate the risk. The top reason bridges fail is a mix of factors that, if they happened individually, would not cause a bridge to collapse. However, when they take place all at once, they result in devastating consequences.

Category	Subcategories
Hydraulic	Flood, Scour, Debris, Ice, Drift, & Dam Failure
Collision	Auto, Truck, Barge or Ship, Train Collision or Derailment, & Airplane
Geotechnical	Slide Plane Failure, Foundation Instability, Abutment Collapse, Sink Hole, Consolidation, Anchor Failure, Unreinforced Piers, & Inadequate Soil Compaction
Fire	Fire, Explosions, & Fire and Collision
Deterioration	Concrete, Steel, Decay, Pier, Pile, & Abutment
Overload	Posted, Overload with Deterioration
Nature	Storm, Hurricane, Wind, Tornado, Earthquake, Volcanic Eruption, Avalanche, Freezing, Insect Attack, & Tree Fall
Other	Fatigue, Design Error, Construction, Bearing, Cable Rubbing, Miscellaneous, or Unknown

Table No 1: Bridge collapse hazards

There is no departmental facility in India, where such type of data regarding bridge failure causes; post impact after failure; its consequences are recorded, but Indian bridge management system is formed recently to collect bridge condition inventory data for their maintenance at the proper time as per structural deficiency. But in USA, UK, Canada etc. There are available recorded data about condition inventory data; causes of bridge failure; its consequences etc. With estimation to certain extent. Some bridge failure in India and its causes are shown Table No-2 On basis of available data on websites, Journal, report

A few Bridges failure and causes in India is described in Table No. 2

SI.No.	Bridge Name	Reason of Collapse
1.	Under construction flyover collapse on 28 July 2018 in Varanasi, UP, India	Multiple factors such as faulty design without safety consideration, allow traffic movement under flyover, without consideration of work site proper safety measures and lack of proper oversight contributed to the collapse.
2.	An under-construction over-bridge of the Delhi Metro collapsed at 5 AM on July 12, 2009 at Jamrudpur site in south Delhi	"Design deficiency" was responsible for collapse of an under-construction bridge. The pier cap cantilever part separated from pier shaft after launching the girder on bearing pedestal.
3.	A portion of an under construction bridge of the Delhi Metro collapsed in Laxmi Nagar and fell on passing vehicles, including a bus, in Delhi at about 7:05 AM on Oct 19,2008	Lifting crane mechanical fault leading to the collapse of the 34-metre-long span which fell down.
4.	The Kadalundi River rail disaster was one of the biggest accidents on the Indian railway network in 2001.	One theory of accident was that the pillar of the British-Era Bridge collapsed; another theory was that the bogie frame of the reservation coach which plunged was defective. In fact the reservation coach and the trailing unreserved coaches and a brake van derailed on the bridge.
5.	Valigonda train disaster occurred on 29 October 2005, as flash flood swept away a small rail bridge at Valigonda in Nalgonda district, about 80 km from Hyderabad, on October 29, 2005	Collapsed due to high flood and communication gap between railway-irrigation departments regarding heavy discharging from up stream reservoir. Flash floods caused by heavy rain and the subsequent overflow had breached the embankment, leaving the railway line hanging in the air, and weakened the bridge.
6.	Balance cantilever concrete bridge, linking Chamba town in Himachal Pradesh with Pathankot in Punjab, collapsed on Oct 2018	The collapse of the bridge is because of a default in the construction map or the poor use of material in the construction.
7.	Pier cap cantilever portion fractured on Dec 2019 due to design flaws in superstructure load in service condition of newly constructed Bridge (2009) across Karamnasa River on NH2 connecting UP to Bihar in District-Chandauli, UP.	Pier cap fractured due to inadequate reinforcement; cap thickness to take the load coming from superstructure. This failure due to human error i.e. design flaws, quality failure or supervision deficiency.

SI.No.	Bridge Name	Reason of Collapse
8.	Flyover on National Highway 28 collapsed in Uttar Pradesh's Basti early on Saturday morning 12th August 2018.	The incident occurred after an overloaded truck hit the superstructure part of flyover.
9.	The 190 meter long under Construction Bridge above Aleksandra River in Srinagar Garhwali Pauli district, Uttarakhand collapsed at 3 AM on March 25, 2012.	The incident occurred when the structure collapsed while concrete was being poured into deck slab of the bridge. Casting of deck slab was started from middle span instead of casting the end span first; sequence for construction activities not in line with good engineering practices
10	A 35 meter long portion of a skew slab of the under construction flyover in Surat collapsed from 30 feet height on June 10,2014 , when its shuttering props were being removed.	It means "Bearing pedestal has not been designed for skew slab load coming to the bearing point. CAG observed that the curved span between piers CP-14 and CP-15 of the flyover collapsed due to wrong calculation of reaction forces by the consultant. Its report said that tests of compressive strength of core are found negative. Substandard material was used for construction of collapsed span CP 14-15.
11.	Failure of Vivekananda flyover (Kolkata) at 31st March 2016	It is to be noted that failure has occurred due to design deficiency. The longitudinal beams spanning between the portal hammer head frames had no bracings on the compression flanges to prevent lateral buckling. Such buckling imposed additional horizontal loads on the portal frame box girders. Failure post photograph shows the twisting of steel plate girders placed on top of cantilever girders, which indicated that the failure could have been due to lateral torsional buckling of the girders, as there may be inadequate bracing to their top flanges.

Table No 2: List of some Bridge failure in India

4. Bridge Failure Consequences

The post hazard impact is assessed to obtain vulnerability of the bridge against these hazards and appropriate risk assessment. The consequences of failure, which play an essential role in both qualitative and quantitative risk-based design and assessment and robustness evaluation of bridges. The consequences of failure are a good indicator of the importance of a bridge structure. Only elements of the transportation infrastructure, but they also form part of electricity, telephone, water, gas networks as well (Stimpson 2009). Therefore, the consequences of bridge failures may extend far wider than the boundaries of transportation systems to other forms of critical infrastructure. They can range from casualties and injuries to structural damage, reduction in network functionality and may also extend into environmental as well as societal impact. Table No-3 shows that, in general, consequences resulting from bridge failures may be divided into four main categories: human, economic, environmental and social. Considering these consequences is essential in both qualitative and quantitative risk-based design and assessment. The consequences can generally be divided into direct or indirect. Direct consequences can be associated with possible injuries or fatalities due to the failure as well as with re-construction costs of the bridge, in the case of total collapse, or repair costs, in the case of damage. Indirect consequences, on the other hand, may arise due to loss of functionality of the transportation network following on from the bridge failure and the unavailability of the bridge. These can be associated with traffic disruption and delay costs due to repair works or detour due to complete bridge closure, traffic management costs, social and environmental impact costs etc. In some cases, bridges are not.

The consequences of failure vary significantly from structure to structure, and may depend on a range of factors which are related to the hazard itself, the structure and its utilization, as well as the surrounding environment. First, the source and nature of the hazard leading to the bridge collapse will affect considerably the consequences. It is expected that the greater the magnitude and duration of a hazard, the greater the consequences will be. The bridge type will also influence both its vulnerability and robustness, and, hence, the consequences, which are likely to be sensitive to factors such as the structural form, the material used, age and condition, as well as quality of construction.

Consequence Categories	**Examples**
Human	Fatalities Injuries Psychological damage
Economic	Replacement / repair costs Loss of functionality / downtime Traffic delay / re-routing costs Traffic management costs Clean up costs Rescue costs Regional economic effects Loss of production / business Investigations / compensations Infrastructure inter-dependency costs
Environmental	CO_2 Emissions Energy use Pollutant releases Environmental clean-up / reversibility
Social	Loss of reputation Erosion of public confidence Undue changes in professional practice

Table No -3: Categorization of bridge failure consequences

4.1 *Factors Affecting the Consequences of Failure*

The consequences of failure vary significantly from structure to structure, and may depend on a range of factors; related to the hazard, the structure and its function, and the surrounding Environment.

(I.) **The nature of the hazard** will considerably affect the consequences considered. It is evident that the greater the magnitude and duration of a hazard, the greater the consequences will be. But the type of hazard also plays a role insofar as it may pose additional risks to humans (or animals) through exposure, inhalation or ingestion. For example, a fire will have an adverse influence on mechanical properties, directly affecting the ability of a structure to withstand loads, but may also generate fumes and toxic pollutants which can be dispersed in the atmosphere. Moreover, it is also possible for a hazard to create a chain effect, for example an explosion may be followed or preceded by a fire, an impact may be followed by a fire etc.

(II.) **The properties of the structure** will influence both the vulnerability and robustness of the bridge or any structure. The consequences will be sensitive to factors such as the materials used, bridge type, age, size, height, layout (including ease of evacuation), type of construction and quality of construction.

(III.) In other words, the **location** of a structure will have significant bearing on the consequences arising from any given failure event. In the case of bridges, location is a major factor with regard to failure consequences. The type of road or rail route served by the bridge influences the traffic intensity and, hence, the number of people exposed to any given hazard, as well as the traffic delay costs. As in the case of buildings, the availability of emergency services and accessibility to treatment for injuries will most likely be best in urban areas, but, on the other hand, access in rural areas is likely to be easier and interdependency issues might be less critical. In other words, the **location** of a structure will have significant bearing on the consequences arising from any given failure event.

(IV.) Depending on the **time of day**: For bridges, this factor is equally important, since these structures experience high levels of usage during peak times. Thus, not only the potential for mass casualties is greater but also the likelihood of certain hazards that may lead to failure can also be increased due to higher exposure density. Further temporal variations may occur daily, weekly, monthly, seasonally etc. and it is important to think of correlations between such variations and resulting consequences.

(V.) The **time frame considered** (days/weeks/years) in the consequence analysis will affect significantly its outcome. For example, in order to capture the influence of long-term effects of a bridge failure, consideration should be given to the full period until reconstruction is completed; even beyond that period there are likely to be residual influences that may take many more years before they are completely eradicated. In fact, the bridge failure and its resulting impact on the transportation network may be such that a new long-term equilibrium is reached, markedly different from what existed prior to the original failure.

(VI.) Finally, the **meteorological conditions**, both during and after the failure event, may have some impact on the consequences. In particular air conditions (including wind direction, wind speed, terrain etc.) will influence the level of dispersion of any toxic pollutants, leading to an increase or decrease in the environmental consequences accordingly.

4.2 Consequences Hierarchy

Consequences are diverse, naming a few: life loss, injury, critical or emergency routes, economic loss, environmental concerns, and historical significance. When considering decision management alternatives, a hierarchy is sure to exist on the potential outcomes if a bridge or portfolio of bridges were to experience extreme loadings. Ethical issues arise with comparison of consequence categories but are applicable within a judgment of a hierarchy. Preference of what routes are critical in the event of a major earthquake is an example of how a hierarchy can be utilized in risk management. Each category has both direct and indirect effects. For example, economic loss can have direct cost through litigation and expedited bridge replacement while indirect loss could be stifled economic development and high user cost. Direct consequences are often simpler to measure and records exist of this nature. On the other hand, indirect consequences are inclined to be onerous to collect and complex, as such records are rare at best. Assessment of consequences in this investigation is a framework for evaluating direct life loss in a fault tree risk analysis.

4.2.1 Qualitative Consequences to Life Loss

Qualitatively life loss consequences for bridge failures are mainly a function of the failure cause, structural configuration and traffic characteristics. Failure cause and structural configuration are interdependent on the rate it takes a bridge to collapse, sudden catastrophic or ductile, and length of span(s) that failed. The collapse progression is time dependent and also plays an integral part. Once the probability and nature of failure are determined, the traffic configuration dependent with bridge length or span lengths and width dictate the number of vehicles at risk. The composition of traffic, diurnal flow, vehicle lengths, persons per vehicle, flow rate, density, number of lanes, and stopping sight distance (SSD) all influence the number of individuals at risk in the event of a failure. Composition of traffic relates to the diversity of the traffic, whether it is semi-tractor trailers, transport busses, or passenger vehicles, and a mix. Vehicle length determines the maximum number of vehicles that can feasibility fit on a specific bridge length. Persons per vehicle values convert the vehicles at risk to the population at risk. The flow rate is an estimate of the number of vehicles per hour passing a point, whereas density refers to the number of vehicles on the road. The relationship between the two is the higher the density the lower the flow rate, with the maximum density being gridlock and flow is near zero. The number of lanes is independent of direction but multiplies the at risk vehicles per lane. Last is the SSD, which is the length necessary to stop before running off into the damaged, downed portion or void. These criterions constitute a qualitative life loss in a generic form for the travelled way, and are by no means comprehensive.

4.2.2 Quantitative Consequences to Life Loss

Historically significant bridge failures that have resulted in extreme consequences are in general well researched. Two examples are the Queen Isabella Causeway and the I-35W Bridge in Minneapolis that failed in 2001 and 2007, respectively. The Queen 55 Isabella Causeway bridge failure is unique due to the route being the only vehicle access to the South Padre Island, Texas. Thus, when the failure occurred the residence of South Padre Island had no detour, became isolated and utilities crossing the bridge were severed. Not only were lives loss in the bridge collapse but the entire community became exposed to the consequences of the failure (Wilson, 2003). The Minneapolis I-35W Bridge had a relatively short detour length; however, the ADT of 140,000 is an example of life loss and high user cost from the ensuing metropolitan traffic congestion (Hao, 2010).

4.2.3 Quantification of consequences

Consequences can be measured in terms of damaged, destroyed, expended or lost assets and utilities such as raw materials, goods, services and lives. They may also include intangibles, either from a practical or a theoretical standpoint, especially in the case of social consequences and long-term environmental influences. In general, they are represented through a vector **C** = [C_1, C_2, … C_m], whose elements should be in appropriate units for the type of consequence considered. Where possible, consequences should be expressed in monetary units, though this is not easy to achieve, and may not be desirable or, indeed, universally acceptable.

5. Conclusions

Although thousands of bridges are being constructed every year around the world, only few collapse due mainly to natural factors (flood, scour, earthquake, landslide, wind, etc.) and human factors (improper design and construction method, collision, overloading, fire, corrosion, lack of inspection and maintenance, etc.). Some of these unfortunate incidents result not only in economic loss, but also in loss of human life. Bridge designers try to avoid failures by analyzing the causes of failures and learning from them. The development of new materials, updated efficient forms of substructure and superstructure as well as new technology of construction, leading to longer spans; longer life, is being adopted considering aforesaid failure factors. Now a days, Longer bridge service life i.e. approx. 100 years is due to learning from past bridge failure too. It is the responsibility of the engineers and contractors to acquire the knowledge from every collapse and make sure the next bridge will be safer. A database of bridge failure is used to compare consequence with the failure rate by cause. The failure rate by cause and consequence is being evaluated qualitatively and quantitatively and can be utilized in future fault tree risk analysis and risk management decision making. A database of failures is used to show the hazards bridges have failed from historically, determine the failure rate based on the cause of failure, and formulated a conditional probability of failure accounting for the features under the structure. Consequences of bridge failures were established qualitatively by engineering judgment.

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