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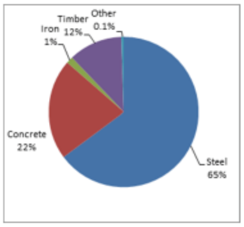

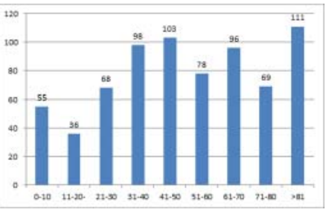

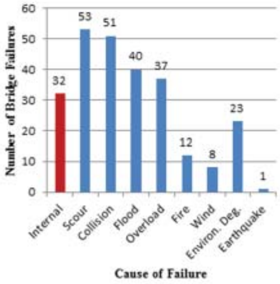

Technical Report MCEER-13-0008

June 15, 2013

This research was conducted at the University at Buffalo, State University of New York and was supported by the Federal Highway Administration under Contract Number DTFH61-08-C-00012.

NOTICE

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George C. Lee,[1] Satish B. Mohan,[2] Chao Huang[3] and Bastam N. Fard[4]

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Preface

MCEER is a national center of excellence dedicated to the discovery and development of new knowledge, tools and technologies that equip communities to become more disaster resilient in the face of earthquakes and other extreme events. MCEER accomplishes this through a system of multidisciplinary, multi-hazard research, in tandem with complimentary education and outreach initiatives.

Headquartered at the University at Buffalo, The State University of New York, MCEER was originally established by the National Science Foundation in 1986, as the first National Center for Earthquake Engineering Research (NCEER). In 1998, it became known as the Multidisciplinary Center for Earthquake Engineering Research (MCEER), from which the current name, MCEER, evolved.

Comprising a consortium of researchers and industry partners from numerous disciplines and institutions throughout the United States, MCEER's mission has expanded from its original focus on earthquake engineering to one which addresses the technical and socio-economic impacts of a variety of hazards, both natural and man-made, on critical infrastructure, facilities, and society.

The Center derives support from several Federal agencies, including the National Science Foundation, Federal Highway Administration, National Institute of Standards and Technology, Department of Homeland Security/Federal Emergency Management Agency, and the State of New York, other state governments, academic institutions, foreign governments and private industry.

The Federal Highway Administration (FHWA) is supporting a study entitled "Principles of Multiple-Hazard Design for Highway Bridges." The project objectives are to establish a number of fundamental design principles and a framework to systematically expand the current AASHTO Load and Resistance Factor Design (LRFD) bridge design specification into a multi-hazard (MH)-LRFD. This is carried out by working closely with Federal Highway Administration experts, the AASHTO Subcommittee on Bridges and Structures (SCOBS) Technical Committee on Loads and Load Combinations (T-5), and with selected individuals who were largely responsible for the development of the current AASHTO LRFD. Several innovative technology developments for the mitigation of and response to extreme events are also part of this project. These include the development of software for a bridge damage database, development of a comprehensive framework for MH-LRFD, extreme hazard load effect calibration, multi-hazard design examples and case studies, traffic optimization software for multiple hazards, freight movement under multi-hazard conditions, development of a curvature sensor for bridge health monitoring, and education materials related to multi-hazard resilient bridges and highway infrastructure.

This report describes the development of a database of hazard events and their damage effects on bridges through a review of available bridge failure documentation. Emphasis is given to the data *sources and an explanation on how the collected information is documented. The objective of this study is to establish data sources for developing load distribution models and bridge damage models for reliability-based formulation of design limit states. Data collected so far, however, are insufficient for accomplishing this objective, due to a lack of specific information on the hazards, bridge design and resulting economic losses in quantitative terms. Gathering such data will require engineering forensic studies on previously damaged bridges. Further, standardized measures should be used to enter data into a database for future events as well as for the results of forensic studies of past failures, one bridge at a time. To re-examine past bridge failures is a tedious and challenging task, but its long-term pay-off can be significant from the viewpoints of bridge safety and reduced economic losses.*

Abstract

Designing bridges to resist extreme hazard load effects has always been a safety concern of AASHTO and the bridge engineering community. This concern has been elevated in recent years because of the perceived increased frequency and intensity of extreme hazards that affect bridges. Some of these hazards have resulted in significant losses; for example, the 2005 Hurricane Katrina had damage exceeding $125 billion in addition to the loss of 1,833 lives.

When a bridge failure occurs, the loss of the bridge structure is only one component of the total loss; its loss can result in much greater national economic consequences than the value of the asset itself. This has highlighted the need to intensify the exploration of design principles and methodologies for the optimal design of multiple hazard (MH) resilient bridges. A research project at the Multidisciplinary Center for Earthquake Engineering Research (MCEER), supported by FHWA since 2008, has been dedicated for this purpose. To pursue this task, it is essential to first establish reasonable bridge damage/failure models. Furthermore, most of the issues in developing or improving current bridge design specifications can be either addressed or improved by the collection and deep understanding of sufficient bridge damage information. Therefore, the initial task is to gather quantitative information of the hazard events and their damage effects on bridges through available bridge failure documentation. This report describes the information collected by the authors, with emphasis given to the data sources and an explanation on how the collected information is documented. The objective of this report is to establish data sources for developing load distribution models and bridge damage models for reliability-based formulation of design limit states. For example, the results of statistical analyses can be used to calibrate and determine a reasonable probability of failure for bridge design under current Load and Resistance Factor Design (LRFD) framework. Data collected so far, however, are insufficient for accomplishing the intended objectives, due to the lack of specific information on the hazards, bridge design and resulting economic losses in quantitative terms. Gathering such data will require engineering forensic studies on previously damaged bridges. A national or international workshop should be organized to establish standard measures for different hazards, and their impact on bridge damage/failures. These standardized measures should be used to enter data into the database for future events as well as for the results of forensic studies of past

failures, one bridge at a time. To re-examine past bridge failures is a tedious and challenging task, but its long-term pay-off can be significant from the viewpoints of bridge safety and reduced economic losses.

Acknowledgment

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SECTION 1

INTRODUCTION

Bridges are primarily designed to carry the vertical loads (non-extreme loads) due to its own weight and traffic (cars, trucks, trains, etc.) over a span or spans crossing waterways, valleys, highways, railways, or other constructed facilities. During the expected service life of a bridge, natural or manmade extreme hazard conditions may arise. These hazard effects, when combined with frequent non-extreme loads, can result in sufficient distress to the bridge structure compromising its capacity to function.

In 2008, a research project at the Multidisciplinary Center for Earthquake Engineering Research (MCEER) was sponsored by the Federal Highway Administration (FHWA) to explore design principles and methodologies in order to develop multiple-hazard (MH) design guidelines. The research program for the multiple-hazard load and resistance factor design (MH-LRFD) consisted of the following components:

1. Collect information on bridge damage and failures due to extreme hazard events.
2. Formulate a theoretical framework to establish MH limit states compatible with AASHTO LRFD.
3. Carry out selected examples on the application of the theoretical framework, and
4. Prepare recommendations on continued research needs.

In fact, the first step, i.e., collection of bridge damage information, plays an important role in each era of development of a bridge design specification. Figure 1-1 shows the role of bridge damage information in the development and improvement of working stress design (WSD). Due to the limited understanding of the nature of hazards and limited technology of monitoring, most of the bridge damage information only includes general descriptions, rough statistical analyses and estimates for economic losses. Even so, this bridge information had guided the bridge design specifications towards a more safe and reasonable design methodology. An example is the importance of spiral or stirrups that attracted wide attention from researchers and engineers after the 1994 Northridge earthquake occurred, in which many bridge columns were found to be damaged due to lack of appropriate confinement. Later on, the specification was improved in the regulation of rebar confinement.

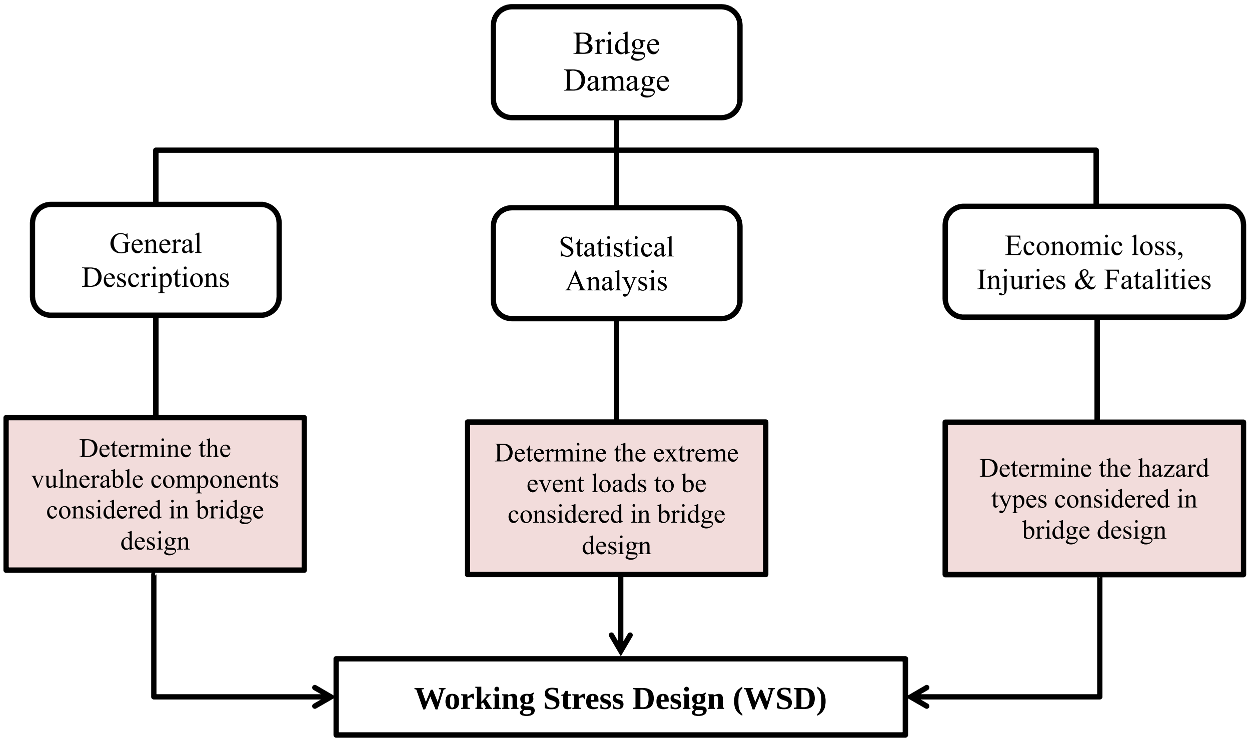


Figure 1-1: Development of Working Stress Design (WSD)

Since the 1990s, as a milestone in the evolution of bridge design philosophy, the establishment of the AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specification [1] further strengthened the role of bridge damage information, as shown in Figure 1-2. The introduction of reliability/probability of failure (PF) helps the engineering community to quantify the safety margins in bridge design. However, the reliability-based formulation of different design limit states was still fraught with many difficulties and delicate issues had to be addressed, such as the estimation and calibration of a reasonable PF, and the quantitative definition of “bridge failure,” etc. Most of these issues can be either addressed or improved by collecting and understanding sufficient bridge damage information.

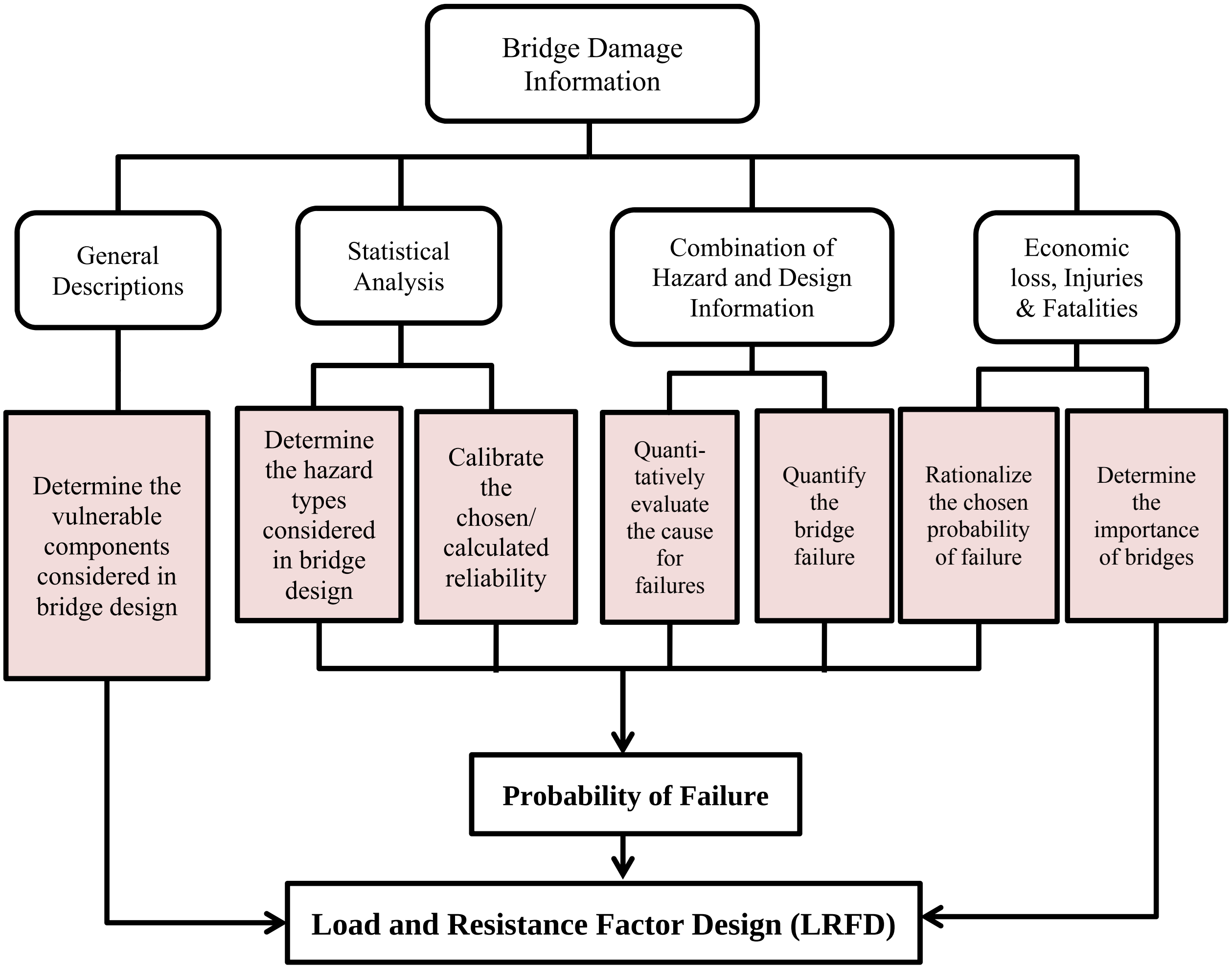


Figure 1-2: Development of Load and Resistance Factor Design (LRFD)

This report is a description of the information collected, from the viewpoint of statistical analyses and general descriptions. It is understandable that available documentation of extreme hazard events and their damaging effects on bridge structures have many different forms, from formal technical reports and books to casual descriptions in newspapers and news releases that may be found from the Internet. Much of the documentation/descriptions do not contain quantitative information useful for forensic studies or bridge damage models.

This report is organized in three main sections following the introduction, which is designated as Section 1. Section 2 describes the sources identified and used to collect the information. They are listed in the References of this report. Section 2 also describes how the extracted information is organized as entries to the bridge damage/failure matrix given in Appendix A. A preliminary analysis of the bridge failures is also included.

In Section 3, information on the causes of bridge damage or failures is briefly described. The causes are categorized into “external causes” and “internal causes,” corresponding to the LRFD design limit state on “loads” and “resistances.” This is understandably not perfect or whole because many bridge failures are due to cascading or combined effects among all possible load and resistance factors.

Although the goal is to collect all available bridge damage/failure information world-wide, data acquired from the open literature and websites showed considerable bias for those available for North America bridges. Therefore, in the description of preliminary findings herein, the North America bridges are used as the base.

Section 4 provides a summary. It offers preliminary observations and conclusions extracted from the preliminary analyses of the database. More detailed and comprehensive conclusions will require more data gathering and quantitative analyses. Also, the lessons learned from these data need to be carefully analyzed in continued studies.

The summary section also emphasizes how to continuously improve the data documentation and its contents so that a more useful electronic database on bridge failures can be developed to improve the AASHTO LRFD Extreme Event Design Limit State equations in the future.

SECTION 2

DATA COLLECTION

2.1 Data Sources

A literature search for this project included: (i) several American Association of State Highway and Transportation Officials (AASHTO) reports [2], (ii) Multidisciplinary Center for Earthquake Engineering Research (MCEER) reports, (iii) articles in scientific journals such as: *Journal of Performance of Constructed Facilities* of the American Society of Civil Engineers, (iv) New York State Department of Transportation (NYSDOT) database, (v) American Concrete Institute articles, (vi) books such as '*Understanding Bridge Collapse*' by Borjan Akesson [3], and '*Failed Bridges*' by Joachim Scheer [4], (vii) articles in newspapers such as *USA Today*, *The New York Times* and *The Jakarta Post*. The bridge damage information in references [2-148] is collected and used to generate the database in Appendix A. In addition, web pages have also been important sources for bridge damage information [149-216]. All of the above cited literature discussed bridge failures; and some of the articles included causes of the collapse and their prevention strategies.

In November 1990, the *ASCE Journal of Performance of Constructed Facilities* published a paper by Harik et al [75] that collected and classified bridge failures that occurred in the United States from 1951 through 1988. This paper aimed at seeing if applying lifetime design to bridges is possible or not.

Wardhana and his colleagues [99] have published three different papers about bridge failures in the United States, in the *ASCE Journal of Performance of Constructed Facilities*. Failure analyses of constructed facilities were carried out for the periods of 1977–1981, 1982–1988, and 1989–2000. The criteria for various analyses have been kept almost consistent to make a reasonable comparison among these three time periods. It should be noticed that most of the bridge failures which have been studied happened in their service life.

Hersi [146] presented a thesis about the analysis of bridge failures in the United States (2000-2008) at Ohio State University in 2008. The objective of the study was to collect and classify bridge failures that occurred in the United States from the years 2000 through 2008.

In 2010, Sharma [148] did a study on bridge failure information. The study included the analysis of 1,814 bridge failures during the past 210 years, from 1800 to 2009. In this report, most of the parameters that the earlier studies used have been kept almost the same for comparative purposes. This data was obtained from two sources: (i) New York State Department of Transportation (NYSDOT) database, and (ii) the database maintained by the Department of Civil Engineering, University of Cambridge, United Kingdom. These databases, though not comprehensive, provide information about a wide variety of bridge failures. A technical paper entitled '*Status of Bridge Failures in the United States (1800-2009)*,' by Sharma and Mohan, was presented at the 2011 Annual Meeting of the Transportation Research Board (TRB) in a poster session [217].

Fard [145] did a study on the potential prevention strategies of bridge failures. The research included a study of 100 major bridge failures which occurred between the years 1818 and 2012. In his report, all the available information about bridge failures such as: year of construction, year of failure, material used, facility type, location, causes of failure, fatalities and injuries, was collected. He has also included suggested prevention strategies that have been reported.

Obviously there are some common bridge failures in these different sources; they were identified before adding to the database of this report. In order to carry out meaningful post-failure studies to benefit future bridge engineering practice, further adequate documentation of the damage and failure condition is needed.

After the tragic collapse of the Thruway Bridge over Schoharie Creek in 1987, the New York State Department of Transportation (NYSDOT) took several steps to reduce and prevent future bridge failures. One of them was the establishment of the Bridge Safety Assurance Unit (BSAU), in 1990, to collect as much information as possible about bridge failures in the United States. Wardhana stated *''The unit has received much information from some States and little to none from others; hence, despite the valuable source of data, the unit has compiled, at this stage, the database does not constitute a complete listing of all failures that have occurred in the United States''* [99].

The NYSDOT database has around 1800 bridge failures and is based on periodic surveys. Also, whenever a bridge failure comes up on the Internet or in the newspapers and other published literature, it is added to the database. NYSDOT performs a survey once every few years and updates the database based on the information that the States provide. The first survey was done in 1992 and the last survey was done in June, 2008; only 18 states have responded back to them. Thus, apparently this database is not a comprehensive or thorough national bridge failure list. Therefore, making any conclusions on failures at a national level, based only on this data, may not be very prudent.

A dissertation was submitted to the University of Cambridge entitled *"Risk Assessment of Existing Bridge Structure"* by Imhof [147]. This dissertation compiled data on bridge collapses. Imhof's database contained 347 recorded bridge collapses. Imhof believes "*this is the most comprehensive bridge collapse database in the world, and has been used in chapter 2 to derive trends of the causes, types and stages of bridge collapse."*

Joachim Scheer published a book on *"Failed Bridges, Case Studies, Causes and Consequences"* [4]. This book covers 536 bridge failures which were categorized based on the type of failure. This book contains a chapter on bridge failures during construction, and includes other failures distinguished by unusual external influences such as vehicle and ship impact, high water and ice, fire and explosions, collapse of scaffolding, and earthquakes.

In recent decades, a number of devastating natural events have caused significant loss of lives and/or economic losses throughout the world. The World Bank has recently estimated that between 1980 and 2011, the total economic losses due to extreme natural events totaled $3.5 Trillion [218] in its report entitled "*Managing Disaster Risk for A Resilient Future*." A more in-depth study of these extreme hazard events suggest that earthquakes, floods, and severe storms resulted in most losses, because they cover areas with many constructed facilities. This is very true for bridges. A vessel collision or a construction error most likely causes the failure of one bridge but a strong earthquake can damage many bridges in the affected area. In the references collected, some only address a single bridge while others (e.g., a reconnaissance report) can cover a large number of bridge failures.

From the viewpoint of collecting data to develop bridge damage models, quantitative information is most important. Thus, references on post-event analysis of damaged/failed bridge(s) are most useful.

2.2 Documentation – Description of Database Tables

The aim of the 1,254 data of bridge failures used in this report, for the period 1980-2012, is to provide a detailed description of each of the bridge failures as reported in the literature. Thus, different information on the failed bridges, such as: description of the bridge, substructure, superstructure, bridge configuration, history of bridge, failure mode, and time and type of failure, and other technical details are gathered in the various tables.

The database might lack some information because it is difficult to find the details about failed bridges in some continents such as Asia and Africa. However, it could be considered a comprehensive bridge failure database because it has included all aspects of the structure of the failed bridges and the resulting causes and damage.

Some major earthquakes were not included in the NYSDOT and Cambridge database, so in a separate effort, detailed information about bridge failures in major earthquakes including the 2008 Wenchuan earthquake in China, 1999 Izmit earthquake in Turkey, 1999 Chi-Chi earthquake in Taiwan, 1995 Kobe earthquake in Japan, 1994 Northridge earthquake in California, 1991 Limon earthquake in Costa Rica, and 1989 Loma Prieta earthquake in California was collected. In this database, 72 bridges that collapsed because of earthquakes after 1980 have been included.

Bridges are vulnerable to floods or hurricanes, so after these catastrophic hazards, many bridges totally or partially collapsed. In 1995, the 500-year Great Flood in Madison County and Green County of north-central Virginia caused many bridges to fail. In 2005, Hurricane Katrina caused the partial or total collapse of many bridges and over 1300 lives were lost. The data of bridge failures for these two major events are added separately to enrich the database.

The total number of bridge failures included in this report is 1,254. However, some of the information was not available in the references or was stated as "unknown." In cases where some of the data were missing, the pie-charts or the tables have less than 1,254 pieces of information for that characteristic. The description of the database of 1,254 failed bridges is tabulated in Table 2-1.

Table 2-1: Description of the Collected Information of 1,254 Bridge Failures (1980-2012)

Data Description		Number of Failures	Percent of Failures
Time of Failure	During Construction	80	6%
	During Service	1,170	94%
	Unknown	4	0%
Region of the Failed Bridges	North America	1,062	85%
	East Asia	85	7%
	Other	101	8%
	Unknown	6	0%
Material Used	Steel	648	52%
	Concrete	277	22%
	Timber	113	9%
	Other	50	4%
	Unknown	166	13%
Type of Failure	Total Collapse	455	37%
	Partial Collapse	368	29%
	Distress	17	1%
	Unknown	414	33%
Total		**1,254**	**100%**

Different aspects of the failed bridges that were included in the database are briefly described in the following sections.

2.2.1 Categorized by Region

The database of 1,254 bridge failures that occurred from 1980 to 2012 has been segmented into three categories as below:

(i) North America
(ii) East Asia
(iii) Other Regions

Since the design specifications/codes and traffic loads vary by geographic regions of the world, this categorization was considered essential for drawing any conclusions. Table 2-1 and Figure 2-1 show this distribution. Eighty five percent (85%) of the failed bridges, in the (1980-2012) database, were located in North America, 7% in East Asia, and 8% in other regions of the world. This factor cannot in anyway divide the total failures to geographic locations. It only reveals the characteristic of the database used in this report. As can be seen, most of the bridge failures occurred in North America. This is probably because of the large accessible amount of information on bridge failures that was compiled from the NYSDOT database, which mostly includes bridge failures in North America.

Although our goal is to collect all available bridge damage/failure information world-wide, data acquired from the open literature and websites showed considerable bias for information available for North America bridges. Therefore, in the description of preliminary findings, North America bridges are used as the baseline.

From this point forward, this report uses only North America bridges in the analyses; these bridges total 1,062, as described in Figure 2-1 and Table 2-3. Table 2-2 tabulates the description of information on (i) Time of Failure, (ii) Material Used, and (iii) Type of Failure for the 1,062 U.S. bridges.

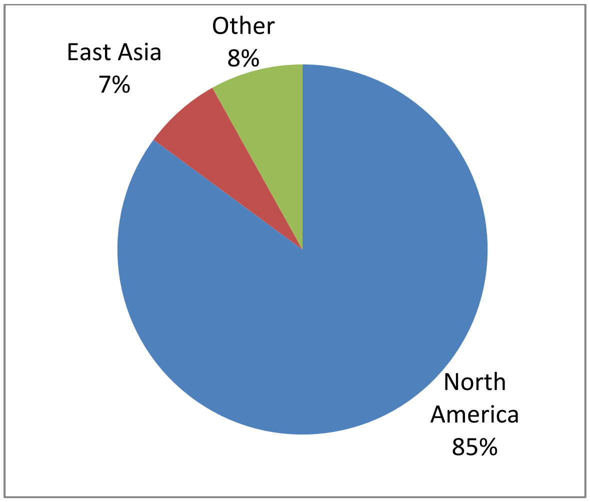


Figure 2-1: Distribution of Failed Bridges by Continents

(1,254 Failed Bridges)

Table 2-2: Description of the Collected Information of 1,062 U.S. Bridge Failures

Data Description		Number of Failures	Percent of Failures
Time of Failure	During Construction	28	3%
	During Service	1003	94%
	Unknown	31	3%
Material Used	Steel	615	58%
	Concrete	205	19%
	Timber	110	10%
	Other	19	2%
	Unknown	113	11%
Type of Failure	Total Collapse	343	32%
	Partial Collapse	285	27%
	Distress	5	0%
	Unknown	429	40%
Total		**1,062**	**100%**

Table 2-3: Distribution of Failed Bridges by Continents (1980 - 2012) in 10-year periods

Time Period	North America	East Asia	Other Regions
2000-2012	253	56	44
1990-1999	430	27	32
1980-1989	372	2	25
Total	**1,062**	**85**	**101**

2.2.2 Categorized by Facility Type

Failed bridges were categorized into four facility types: 1) Highway, which is a major and significant well-constructed road that is capable of carrying reasonably heavy to extremely heavy traffic; 2) Roadway, which in comparison to highway can carry less traffic and also includes all rural routes, 3) Pedestrian, and 4) Railway. Most of the time, it was hard to distinguish between highway and roadway bridges because of their mostly common characteristics. While the failures of pedestrian or railway bridges have usually resulted in more fatalities in comparison to roadway or highway bridges, the numbers of roadway or highway bridge failures are much greater, as can be seen in Table 2-4 and Figure 2-2.

Only 799 of the 1,062 failed bridges in the U.S. reported the 'type of facility'. Out of these 799 failures, ninety one percent (91%) occurred on roadways as opposed to 6% on highways, 2% on railways, and 1% on pedestrain bridges, as shown in Figure 2-2. Many roadway bridges were built many years ago before the introduction of expressways, and therefore their number is high. Also, most of the existing bridges are roadway and highway bridges, and these bridges are generally subjected to more severe and frequent loads than pedestrain and railway bridges.

Table 2-4: Distribution of Bridge Failures by Facility Type

Facility Type	Number of Failure
Roadway	725
Highway	47
Pedestrian	8
Railway	19
Unknown	263
Total	**1,062**

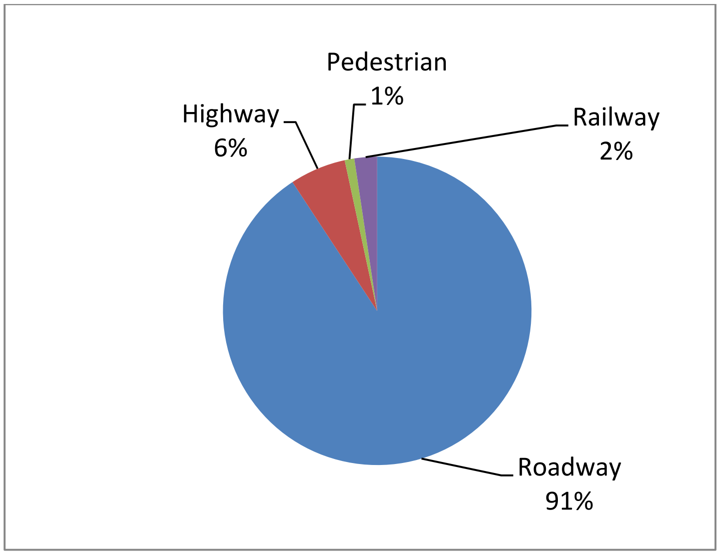


Figure 2-2: Distribution of Bridge Failures by Facility Type in U.S.

(799 Failures, 1980-2012)*

* Only 799 of the 1,062 failed bridges in the U.S., reported the Type of Facility.

2.2.3 Categorized by Material Type

It was considered important to obtain a general idea about the type of structure of the failed bridges and the material used (Steel, Concrete, Iron, Timber, and Stone, etc.). The 1,062 bridge failures in this report's database were comprised of the materials listed in Figure 2-3 and in Table 2-5. Sixty five percent (65%) of the 1,062 bridges that failed in the U.S. after 1980 were made of steel, 22% were concrete bridges, and 12% were timber bridges.

Table 2-5: Distribution of Bridge Failures by Material Type

Material	Number of Failure	Existing Bridges in U.S.*
Steel	615	182,706
Concrete	205	398,474
Iron	14	1,497
Timber	110	22,724
Other	5	1,974
Unknown	113	-
Total	**1,062**	**607,375**

*Source: National Bridge Inventory, FHWA

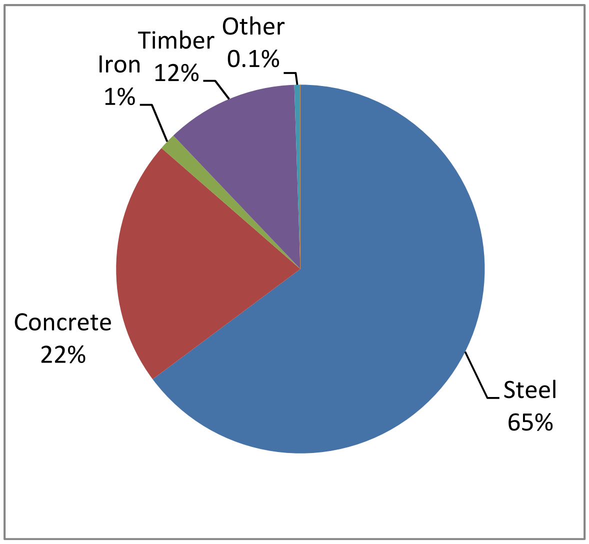


Figure 2-3: Distribution of Bridge Failures by Type of Material Used

(949 Failures, 1980-2012) *

* Only 949 of the 1,062 failed bridges in the U.S. reported the Type of Material used.

The material distribution of the existing bridges in the U.S. is shown in Figure 2-4 and Table 2-5, obtained from National Bridge Inventory (NBI) [50]. Although there are more concrete bridges (65%) than steel bridges (30%) in the U.S., steel bridges dominate the bridge failures perhaps due to two possible reasons: (i) in general, most of the bridges built earlier were made of steel and thus have a higher average age than concrete or other bridges. Earlier when these bridges were built, the design knowledge and codes were not sophisticated and were under developed, and (ii) the annual maintenance and inspections are more essential for steel bridges since they are more vulnerable to environmental degradation.

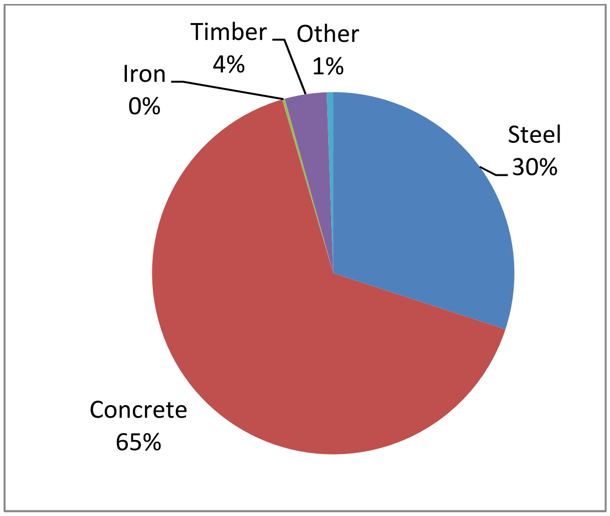


Figure 2-4: Material Types of the Existing Bridges in U.S.

(Total 607,375, as of 2012) Categorized by the Type of Bridge Structure

Structural type of the failed bridges included several categories as listed below:

- Arched
- Truss-arched
- Suspension
- Cable-stayed
- Through-truss
- Girder
- Culvert

Table 2-6 shows the number of bridge failures by their structural type. This table also includes the total number of existing bridges in the U.S. by their structural type. Percentages of different structural types of failed bridges are shown in Figure 2-5 and the percent distribution of the total bridges in the U.S. by structural type is shown in Figure 2-6. The most common structural type is Girder Bridge at 58%, followed by Through-truss Bridge at 29%. Comparing the two distributions shown in Figure 2-5 and Figure 2-6 indicates that (i) Girder bridges have the greatest number of failures (58%), in fact they are in proportion to their population of existing bridges at 61% (Figure 2-6), and (ii) truss bridges are much more vulnerable than girder bridges, because the truss bridges produced 29% of the failures while they occupied only less than 1% of the total population of existing bridges. The reason is similar to that of steel bridges. Therefore, regular inspections for truss bridges are extremely important for the safety of the entire highway systems.

Table 2-6: Distribution of Bridge Failures by Structural Type

Structural Type	Number of Failures	Existing Bridges in U.S.
Arched	27	7,125
Truss-arched	2	444
Suspension	10	96
Cable-stayed	3	45
Through-truss	261	444
Girder	526	366,710
Culvert	8	133,623
Other	70	98,888
Unknown	155	-
Total	**1,062**	**607,375**

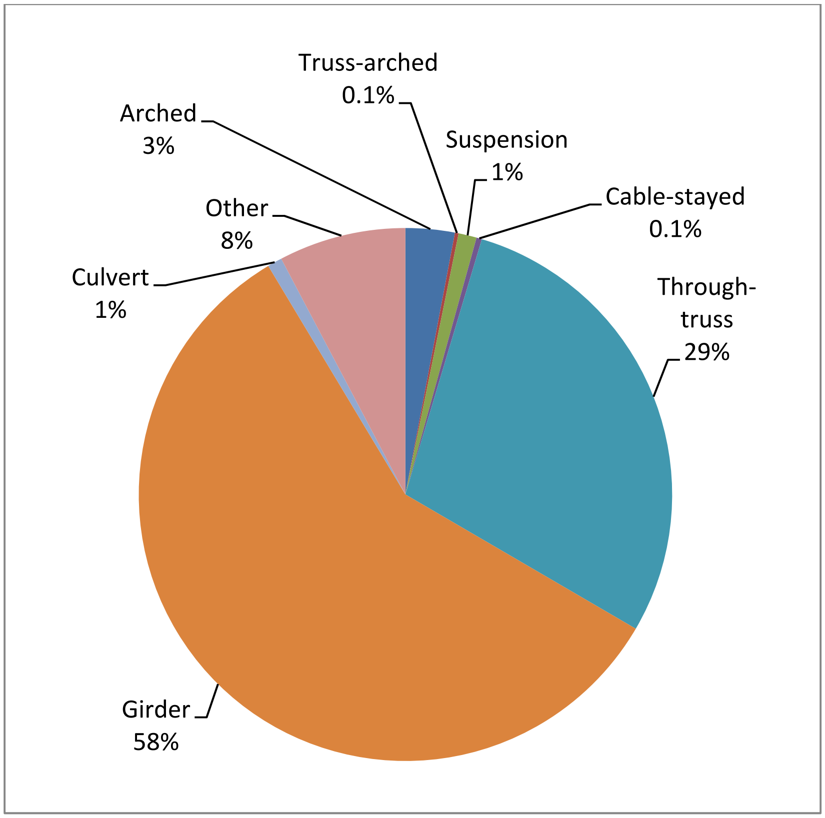


Figure 2-5: Structural Type of the Failed Bridges

(907 Failures)*

* Only 907 of the 1,062 failed bridges in the U.S. reported the type of structure.

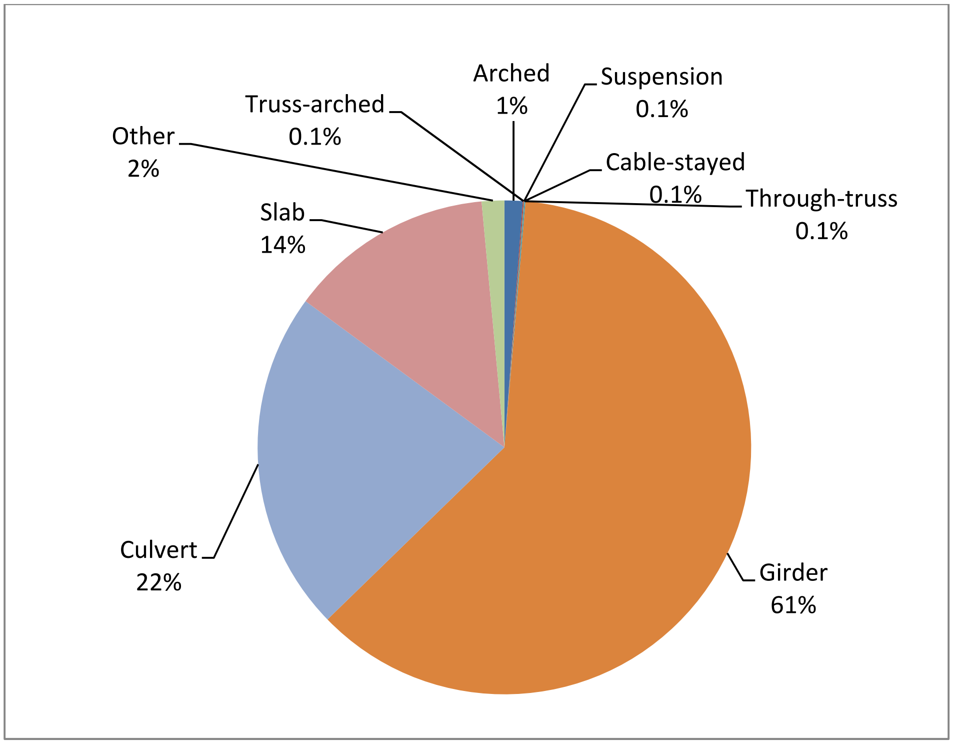


Figure 2-6: Distribution of Existing Bridges in U.S. by Structural Type

(Total 607,375, as of 2012)

The following categories were included in the girder type of bridges:

- Composite
- Slab (Voided)
- T-beam (cast-in-place)
- I-beam (precast)
- I-beam (pre-stressed)
- Wide-flange beam
- Concrete box (cast-in-place)
- Concrete box (segmental)
- Concrete box (pre-stressed)

- Concrete box (precast)
- Steel box
- Steel plate girder
- Slab (solid)

Support of the structure (simply, continuous, cantilever), substructure details, and superstructure details of the bridges were also gathered in detail.

2.2.4 Categorized by Age

To determine the maintenance and inspection procedures, the facility type and the daily traffic volumes were found to be of secondary importance in comparison to age [67]. Finding the year of failure in the database was easy as most of the bridge failures come with the year of collapse, but the exact year of construction of the failed bridges as reported might be difficult to determine.

Of the 1,062 bridges included in this report, the age data was available for 714 bridge failures; the age distribution of these 714 failed bridges, in 10-year intervals, is given in Table 2-7 and Figure 2-7. Three hundred fifty-four (354) of the 714 failed bridges were older than 51 years. For a full understanding of the modes of failure and the causes of failure, it is necessary to know the historical data about repairs, retrofitting, and lifetime maintenance for each of the bridges that failed. This data was not collected in this research, and needs to be collected in future research. This will help in designing appropriate prevention strategies.

The number of bridge failures, in each decade, shown in Figure 2-7, including all types of bridges, will be more revealing to plot such age distribution for:

(i) Major material types
    - Steel
    - Concrete
    - Timber
    - Iron.

(ii) Major structural types

- Arched
- Truss-arched
- Suspension
- Cable-stayed
- Through-truss
- Girder
- Culvert

(iii) Material-Structure types

- Steel - Arched
- Steel - Truss-arched
- Steel - Suspension
- Steel - Cable-stayed
- Steel - Through-truss
- Steel - Girder
- Steel - Culvert
- Concrete - Arched
- Concrete - Through-truss
- Concrete - Girder
- Concrete - Culvert
- Timber - Through-truss
- Timber - Girder
- Iron - Through-truss
- Iron - Culvert
- Other - Arched
- Other - Cable-stayed
- Other - Girder

Table 2-7: Age Distribution of Failed Bridges *

Age at Failure	Number of Failed Bridges
0-10	55 (8%)
11-20-	36 (5%)
21-30	68 (10%)
31-40	98 (14%)
41-50	103 (14%)
51-60	78 (11%)
61-70	96 (13%)
71-80	69 (10%)
>81	111 (16%)
Unknown	348
Total	**1,062**

* Age data was available for 714 of the 1,062 bridges in the database.

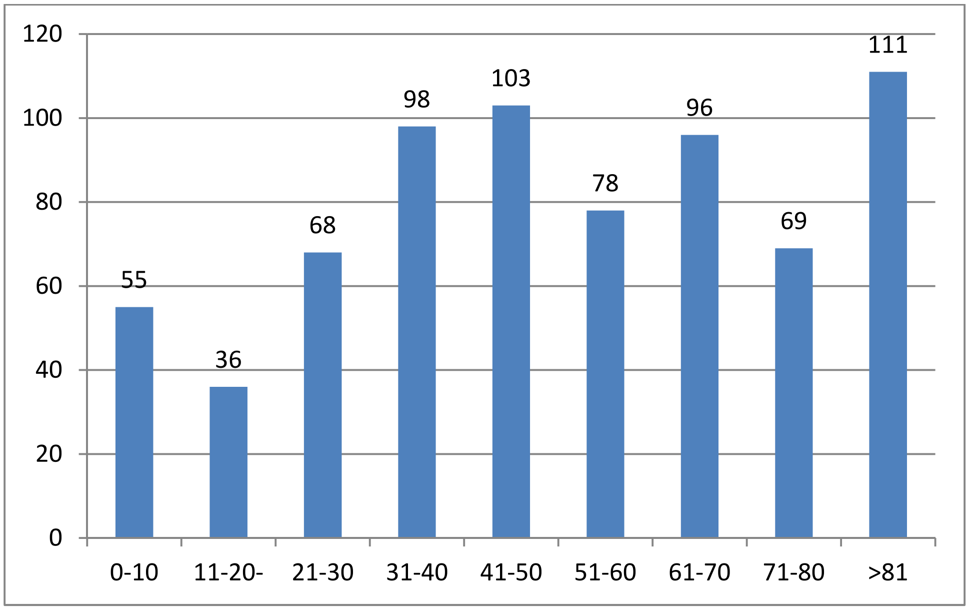


Figure 2-7: Age Distribution of the Failed Bridges

It was considered important to further classify the ages at failure by the type of the facility and the material used. Table 2-8 provides the average age for each of the facility type - material used combinations. Table 2-9 shows the average age of the failed bridges for each of the structure type-material used combinations.

The average ages of the failed bridges for the material used – structural type combinations, as in Table 2-9, were further stratified by the facility type, and are tabulated in Table 2-10.

Table 2-8: Average Age (years) and Number of Failed Bridges for each Facility Type - Material Used Combination

Facility Type	Steel	Concrete	Timber	Iron	Others	Average Age
Roadway	54.7 (396)	47.9 (177)	59.8 (72)	79.2 (10)	68.75 (10)	54
Highway	43.5 (22)	43.57 (20)	- (0)	- (0)	- (3)	40.6
Pedestrian	1 (3)	12 (3)	- (0)	106 (2)	- (0)	31.4
Railway	68 (13)	- (0)	73 (1)	121 (2)	- (0)	74.9
Unknown	88 (165)	- (3)	26 (37)	- (0)	- (1)	75.2
Average Age	63.5	46.2	48.5	89	49.1	51.7

Note: Numbers in parentheses give the number of failed bridges for the cell combination.

Table 2-9: Average Age (Years) and Number of Failed Bridges for each Structure Type - Material Used Combination

Structure	Steel	Concrete	Timber	Iron	Other	Average Age
Arched	40.9 (9)	61.7 (12)	-	-	11 (1)	50.9
Truss-arched	40 (2)	-	-	-	-	40
Suspension	45.1 (8)	-	-	-	-	45.1
Cable-stayed	-	-	-	-	26 (3)	26
Through-truss	73.7 (203)	44.3 (4)	69.1 (15)	96.8 (13)	-	74.2
Girder	45.9 (329)	43.7 (149)	48 (36)	-	69.8 (5)	45.6
Culvert	22 (3)	74.5 (4)	-	6 (1)	-	46.3
Average Age	55.8	45.7	54.2	90.3	48.7	54.1

Note: Numbers in parentheses give the number of failed bridges for the cell combination.

Table 2-10: Average Age of the Failed Bridges for Each Material Type-Structure Type Combination for Each of the Four Facility Types

Material Used - Structure Type Combination	Facility Type			
	Highway	Roadway	Railway	Pedestrian
Steel - Arched	24 (3)	49.7 (4)	-	-
Steel - Truss-arched	40 (2)	-	-	-
Steel - Suspension	-	45.3 (4)	-	1 (2)
Steel - Cable-stayed	-	-	-	-
Steel - Through-truss	-	75.1 (130)	68 (9)	-
Steel - Girder	50.1 (15)	44.8 (225)	-	50 (1)
Steel - Culvert	-	22 (3)	-	-
Concrete - Arched	-	61.7 (12)	-	-
Concrete - Through-truss	45 (1)	44 (3)	-	-
Concrete - Girder	37.6 (17)	45.1 (125)	-	12 (3)
Concrete - Culvert	-	74.5 (4)	-	-
Timber - Through-truss	-	74.1 (11)	-	-
Timber - Girder	-	46.6 (24)	-	-
Iron - Through-truss	-	88.4 (9)	121 (2)	106 (2)
Iron - Culvert	-	6 (1)	-	-
Other - Arched	-	11 (1)	-	-
Other - Cable-stayed	26 (3)	-	-	-
Other - Girder	-	69.8 (5)	-	-

Note: Numbers in parentheses give the number of failed bridges for the cell combination.

2.2.5 Categorized by Type of Failure

The types of bridge failures have been categorized into: (i) total collapse, which means all primary members of a span or several spans have undergone severe deformation such that no travel lanes are passable, and (ii) partial collapse, which means all or some of the primary members of a span or multiple spans have undergone severe deformation such that the lives of those traveling on or under the structure would be in danger. The last type of failure is (iii) distress, which means some members of the bridge cannot bear the load and just by deformation show the need for rehabilitation while the bridge is still alive and usable. The distribution of the bridge failures by the type of failure is shown in Figure 2-8. Fifty four percent (54%) of the bridges had a total collapse, 45% had partial collapse, and only 1% was reported to have distress failures.

The key issue here is the definition of the various degrees of partial collapses. Quantitative information is needed to establish damage models for bridges.

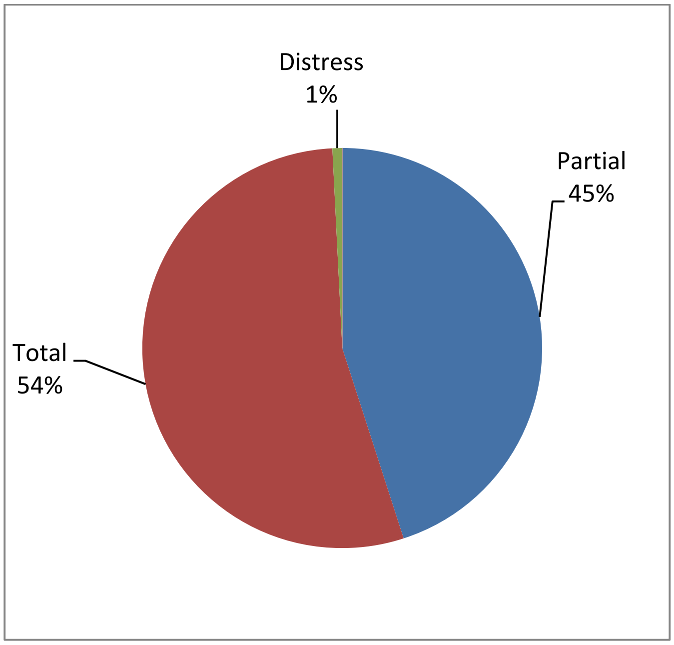


Figure 2-8: Bridge Failures by the Type of Failure

(633 Failures, 1980-2012)*

* Only 633 of the 1,062 failed bridges in the U.S. reported the type of failure.

2.2.6 Categorized by Time of Failure

Ninety seven percentage (97%) of the bridge failures occurred during their service life, while only 3% failed during construction, as shown in Figure 2-9.

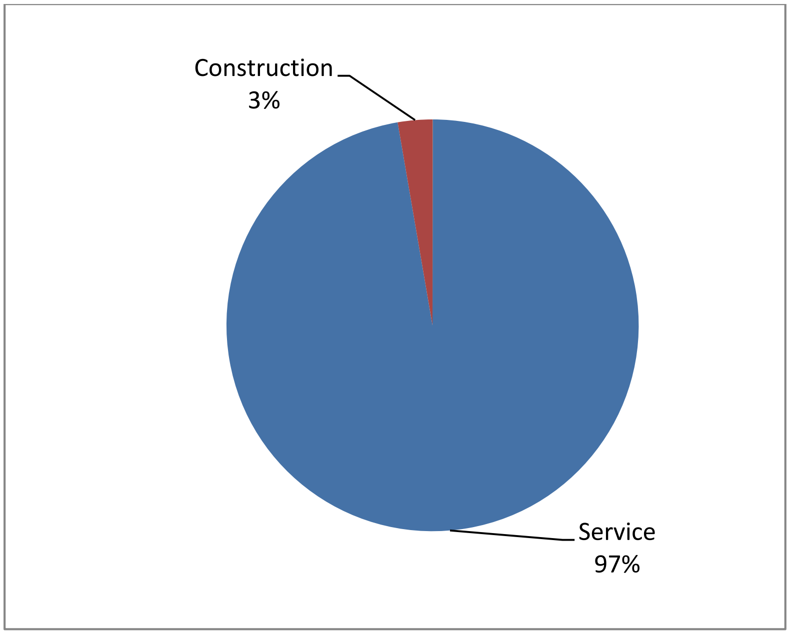


Figure 2-9: Bridge Failures by Time of Failure

(633 Failures, 1980-2012) *

* Only 633 of the 1,062 failed bridges in the U.S. reported the time of failure.

2.2.7 Categorized by Fatalities and Injuries

Most of the time, collapse of a bridge is not predictable but when it fails, it usually causes several injuries and fatalities. The cumulative damage of bridge failures can include (i) deaths and (ii) injuries to many people, as well as (iii) property damage worth thousands to millions of dollars. After a bridge collapse, the economy is affected both in the short-term because of the cost of construction of a new bridge with new materials and design, and also the long-term because of the cost of using a temporary route or detour until the new bridge is ready. As an example, the Hyatt Regency hotel walkway that collapsed on Friday July 17, 1981 in Kansas City, Missouri, caused collapse of two connected walkways; due to faulty design, 114 people were killed and 216 others were injured. Until the collapse of the World Trade Center in 2001, this incident was the most catastrophic failure with the most fatalities and injuries [200].

2.2.8 Categorized by Causes

A bridge collapses when the carrying load is more than its capacity and its resistance. The principal causes of bridge failures have been classified into three categories: (i) internal causes of failure, (ii) external causes of failure, and (iii) cascading failures as mentioned earlier regarding the LRFD design limit state on “loads” and “resistances.”

The internal cause of failure is directed to the capacity of the bridge and consists of: faulty design, error in construction, low quality materials, and lack of maintenance. The external causes of failure are directed to the demand of the bridge and consists of scour, flood, earthquake, fire, collision, wind, overload, settlement, and environmental degradation of members [66].

A cascading failure is a failure of a bridge in which the failure of one element can trigger the failure of successive elements. Many bridge failures are attributed to a simple cause, while the full extent of the main cause of the failure is often unknown. Sometimes it is collision and fire together and sometimes a bridge failed in earthquake because of flawed design. State Route 14 Interchange with Interstate 5 (the Golden State Freeway) collapsed under the Northridge earthquake in 1994. This interchange was designed in 1968 and was under construction when the 1971 San Fernando earthquake occurred. Because of the earthquake, one ramp totally collapsed and two others were damaged. After that earthquake, the damaged portions were repaired without any special rehabilitation and the third one was constructed with some seismic retrofitting. Twenty three (23) years later, both of the ramps that were repaired at the time of the 1971 earthquake collapsed in the Northridge earthquake, while the third ramp was able to sustain the earthquake load [85], because it was constructed with seismic retrofitting.

2.3 Preliminary Analysis of Bridge Failures

Although the goal was to collect all available bridge damage/failure information world-wide, data acquired from the open literature and websites showed considerable bias for data available for North America bridges. Therefore, in the description of preliminary findings, North America bridges are used as the baseline.

The frequency of the different types of bridge failures by different causes of failures are tabulated in Table 2-11, and the different causes for each of the material types are tabulated in Table 2-12. It can be seen that total collapse dominates bridge failures due to flood, overload and scour. Thus, bridges subjected to these hazards need to be more carefully designed or applied with appropriate countermeasures.

Some of the causes of bridge failures are really cascading failures but at this time, information about them is not available.

The total number of U.S. bridge failures in this report is 1,062 and all of them happened after 1980. More in-depth analyses are needed in order to draw meaningful conclusions. For instance, concrete bridges seem to be more vulnerable to earthquake hazard than steel structures, which might be because more concrete bridges are built in high seismic regions from the viewpoint of practical experience and traditions.

Table 2-11: Failure Types of Failed Bridges for Each of the Causes of Bridge Failures

Causes of Failure	Failure Types		
	Total Collapse	Partial Collapse	Distress
Design Error	38% (8)	52% (11)	10% (2)
Lack of Maintenance	67% (2)	33% (1)	0% (0)
Deficiency in Construction	32% (10)	65% (20)	3% (1)
Material Defect	23% (3)	46% (6)	31% (4)
Earthquake	38% (6)	63% (10)	0% (0)
Scour	50% (61)	50% (60)	0% (0)
Flood	75% (83)	25% (27)	0% (0)
Collision	39% (44)	60% (68)	1% (1)
Environmental Degradation	29% (12)	69% (29)	2% (1)
Overload	76% (71)	24% (23)	0% (0)
Fire	50% (12)	50% (12)	0% (0)
Wind	78% (35)	22% (10)	0% (0)

Note: Number in parentheses gives the number of failed bridges for the cell combination.

Table 2-12: Material of Failed Bridges for Each of the Causes of Bridge Failures

Causes of Failure	Material Used		
	Steel	Concrete	Other
Design Error	72% (13)	28% (5)	0% (0)
Lack of Maintenance	33% (1)	33% (1)	33% (1)
Deficiency in Construction	37% (10)	48% (13)	15% (4)
Material Defect	81% (13)	13% (2)	6% (1)
Earthquake	8% (1)	85% (11)	8% (1)
Scour	62% (122)	26% (51)	12% (24)
Flood	63% (174)	23% (65)	14% (38)
Collision	77% (96)	15% (19)	7% (9)
Environmental Degradation	63% (41)	9% (6)	28% (18)
Overload	63% (83)	11% (15)	26% (34)
Fire	45% (13)	17% (5)	38% (11)
Wind	46% (6)	31% (4)	23% (3)

Note: Number in parentheses gives the number of failed bridges for the cell combination.

SECTION 3

CAUSES OF BRIDGE FAILURES

In 2003, Wardhana published a paper related to bridge failures in the United States between 1989 and 2000. Five hundred three bridge failures were studied in this research. Flood and scour were the most common causes of bridge failures at 53%, although it should be noted that a major flood disaster occurred in 1993. In this study, 12% of the bridges failed because of collision with any type of truck, trains, and ships. Overload at 9% and environmental degradation at 8.5% were mentioned as the third and fourth frequent causes of bridge failures during these years. Internal causes had a small part in bridge failures in this study [99].

To provide a general idea about the causes of bridge failures, a comparison between the number of failed bridges vs. causes of failure in the U.S. was conducted and the results are presented in Figure 3-1, Figure 3-2, Figure 3-3, and Table 3-1 by 10-year intervals. It is interesting that the top five causes of bridge failures in this report are exactly the same as in the Wardhana study. In this report, flood and scour at 47% are the most common causes of bridge failures, collision at 15% has the second place, and overload at 13% has the third major cause of bridge failures. Similar to the Wardhana study, the fourth cause of failure is environmental degradation at 7%. Note that although the period of this report is between 1980-2012 and the Wardhana study was between 1989-2000, the trends of both studies are almost the same.

Of the 1,062 total bridge failures during the 1980-2012 period, the histograms shown in Figure 3-1, Figure 3-2, and Figure 3-3 include 1,055 failures; the causes of seven failures are not distinctly defined in the data sources and are listed as ‘other causes’ in Table 3-1. Of the 1,055 bridge failures, 257 occurred during 2000-2012, 419 during 1990-1999, and 379 during 1980-1989.

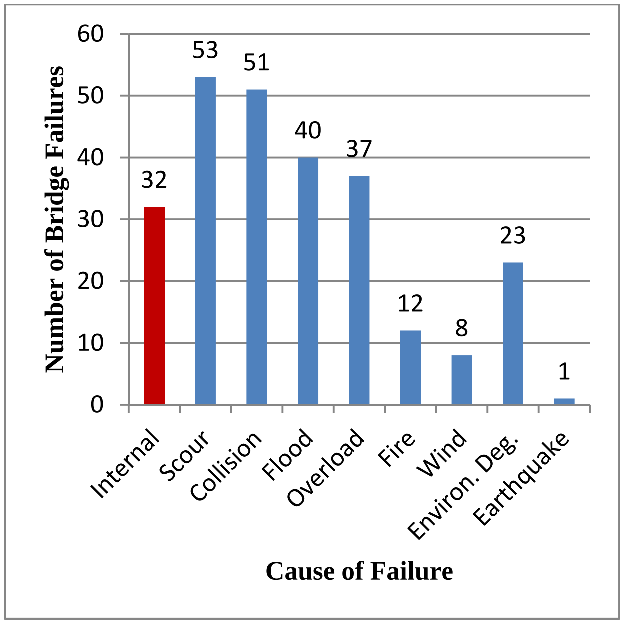


Figure 3-1: Number of Failed Bridges vs. Cause of Failures between 2000 - 2012

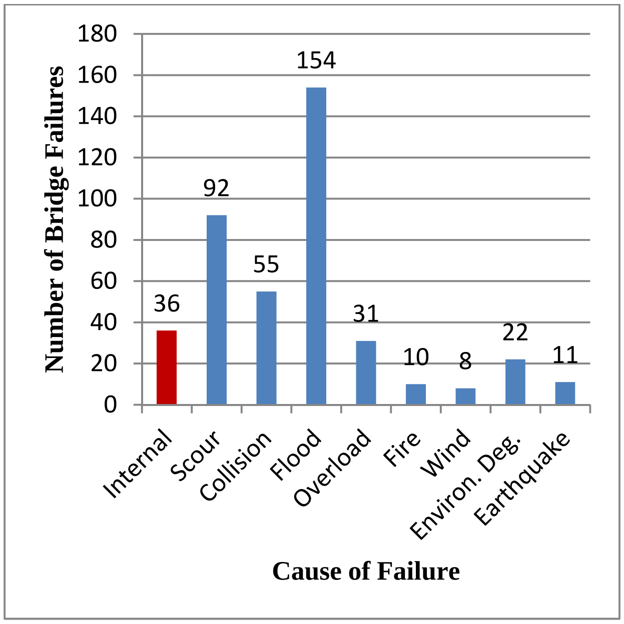


Figure 3-2: Number of Failed Bridges vs. Cause of Failures between 1990 - 1999

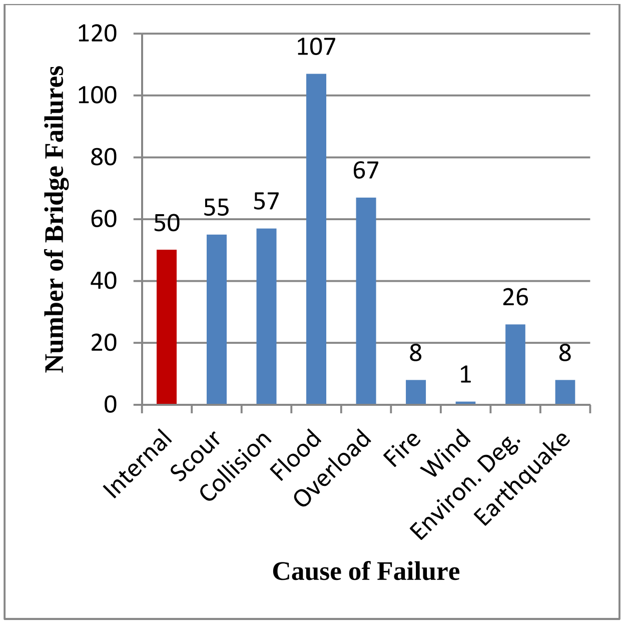


Figure 3-3: Number of Failed Bridges vs. Cause of Failures between 1980 - 1989

Table 3-1: Number of Failed Bridges vs. Causes of Failure, by 10-Year Intervals

(1980-2012)

Causes of Failure	2000-2012	1990-2000	1980-1990	Total	Percent
Internal Causes	32	36	50	118	11.1%
Scour	53	92	55	200	18.8%
Collision	51	55	57	163	15.3%
Flood	40	154	107	301	28.3%
Overload	37	31	67	135	12.7%
Fire	12	10	8	30	2.8%
Wind	8	8	1	17	1.6%
Environmental Degradation	23	22	26	71	6.7%
Earthquake	1	11	8	20	1.9%
Others	2	3	2	7	0.7%
Total	259	422	381	1,062	100.0%

3.1 Internal Causes

Relating a bridge collapse to internal causes needs forensic investigations and experiments to be conducted. Thus, declaring exact numbers of failures to internal causes is difficult and sometimes unrealistic. However, in this report, it was attempted to tabulate internal causes versus material used, facility type, and structural type, as shown in Table 3-2 and Table 3-3. Table 3-4 relates the type of failure and the time of failure to each of the internal causes. It was found that:

(i) Most of the steel bridges failed due to design error, material defect, and deficiency in construction. The major internal causes for concrete bridges were deficiency in construction and design error.

(ii) Among the facility types, deficiency in construction caused most failures on roadway bridges. Design error was the second greatest cause for roadways as well as highways.

(iii) Most of the girder bridges failed due to deficiency in construction, followed by design error and material defect.

(iv) Deficiency in construction caused most partial and total collapses followed by design error.

(v) Most failures during construction (30 out of 34) were caused by deficiency in construction. For in-service failures, material defect was the prime internal cause followed by design error.

Table 3-2: Number of Bridge Failures due to Internal Causes – Material Used and Facility Type

Internal Causes of Bridge Failures	Material Used			Facility Type			
	Steel	Concrete	Other	Roadway	Highway	Pedestrian	Railway
Design Error	13	5	0	13	6	2	1
Lack of Maintenance	1	1	1	2	1	0	0
Deficiency in Construction	10	13	4	24	6	1	0
Material Defect	13	2	1	10	4	0	1
Total	**37**	**21**	**6**	**49**	**17**	**3**	**2**

Table 3-3: Number of Bridge Failures due to Internal Causes - Structural Type

Internal Causes of Bridge Failures	Structural Type						
	Arched	Truss-arched	Suspension	Cable-stayed	Through-truss	Girder	Culvert
Design Error	3	1	1	0	2	9	0
Lack of Maintenance	0	0	0	0	1	2	0
Deficiency in Construction	3	0	1	1	1	17	0
Material Defect	4	0	2	0	3	8	0
Total	**10**	**1**	**4**	**1**	**7**	**36**	**0**

Table 3-4: Number of Bridge Failures due to Internal Causes - Type and Time of Failure

Internal Causes of Bridge Failures	Type of Failure			Time of Failure	
	Total	Partial	Distress	Service	Construction
Design Error	8	11	2	13	4
Lack of Maintenance	2	1	0	3	0
Deficiency in Construction	10	20	1	8	30
Material Defect	3	6	4	17	0
Total	**23**	**38**	**7**	**41**	**34**

3.1.1 Design Error

The major goal of current structural design procedures is to ensure that bridges do not experience any failure (strength, extreme event, service, and fatigue limit states) during their service life. Construction errors or lack of maintenance can bring down a bridge but some bridges are doomed to collapse during construction because of faulty design [189].

An adequately designed bridge can properly sustain unexpected extreme event loads such as earthquakes. Stiffness, deformability, and energy dissipating systems are some important factors which should be considered in order to have a serviceable and safe bridge [100].

However, most of the time, relating the cause of a bridge collapse to faulty design needs detailed forensic investigations. In this study, among all of the 1,062 bridge collapses after 1980, 21 bridge collapses were detected to happen because of defect in design. Further, 13 of these 21 bridges failed during their service life and four bridges collapsed during construction. The interesting point about the bridges that collapsed during service life is that they all were designed before 1980.

Bridge collapses during the service life can be categorized based on the structural elements (connection, girder, column, truss, foundation, and bearing) that failed. Table 3-5 and Figure 3-4 show which of these elements had a major part in the collapse of bridges. On the basis of the number of failures due to design error, as seen in Table 3-5, it can be suggested that during the next revision of codes, more guidance is needed in the design and retrofitting of girders, connections, and columns to avoid future failures. Note that this distribution does not include all of the 21 bridge failures caused by faulty design, because some data was missing.

Table 3-5: Number of Bridge Components Failed due to Design Error

Design Components	Number of Failures due to Design Error
Column	3
Girder	5
Truss	1
Bearing	0
Connection	3
Foundation	2
Other	1
Unknown	6
Total	**21**

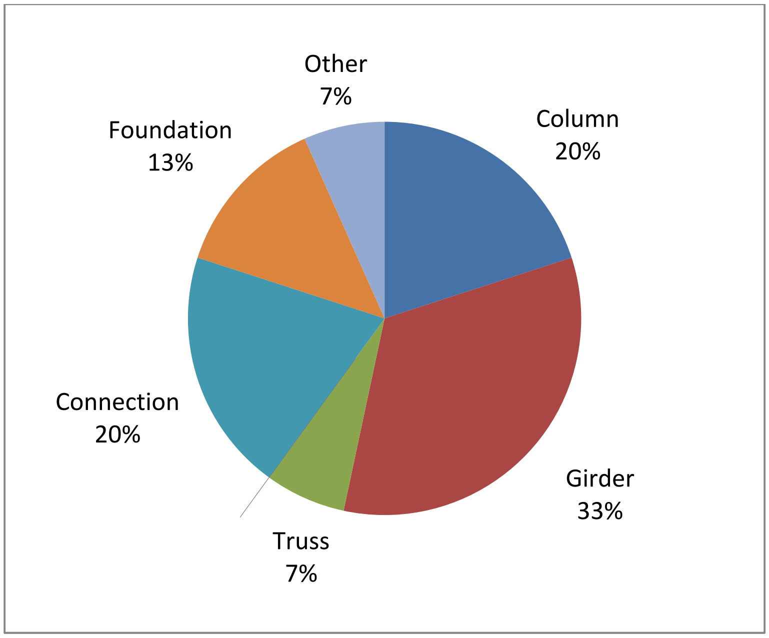


Figure 3-4: Bridge Components Failed due to Design Error

(15 Failures)*

* Only 15 of the 21 failed bridges due to design error was reported.

Table 3-6 shows the failure modes of bridges failed due to design error. Figure 3-5 shows that the percentages of partial collapses and the total collapses were 52% and 38%, respectively. As shown in Figure 2-8, total collapse (54%) is more common in bridge failures.

Table 3-6: Failure Modes of Bridges Failed due to Design Error

Type of failure	Number of failures due to design error
Partial	11
Total	8
Distress	2
Total	**21**

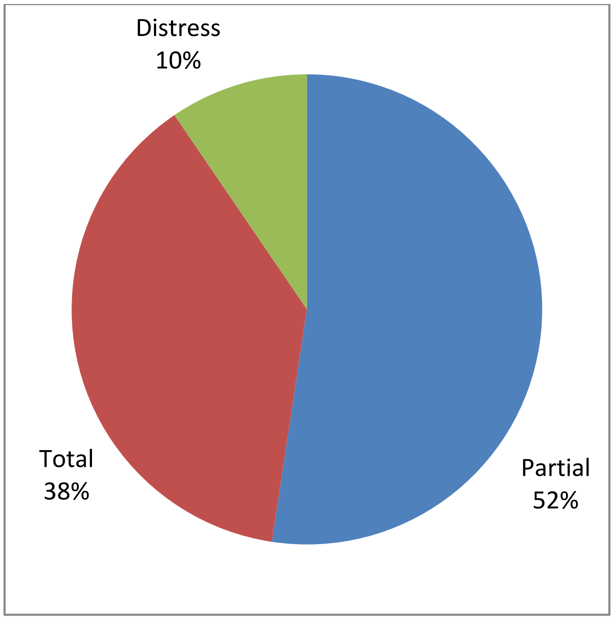


Figure 3-5: Types of Failure due to Design Error

(15 Failures)

In 2003, the Sgt. Aubrey Bridge, which was constructed in 1960 at Latchford, Ontario, Canada over the Montreal River, collapsed partially because of the failure of three vertical hanger rods that supported the deck. This can be attributed to a fatigue-induced fracture. The design of connections and especially pins in the hangers was faulty and caused bending fatigue stresses in rods [109].

During the construction of the Injaka Bridge at Mpumalanga, South Africa, over the Ngwaritsane River, in 1998, one of the bearing pads was punched. The design of the temporary bearings was insufficient and placed incorrectly. This design deficiency of the bridges was found after further investigation; however, after the failure of the bearings, the failure of the bridge was inevitable [113].

Case Study: Collapse of I-35W Bridge over the Mississippi River in Minneapolis

In 2007, the interstate highway bridge I-35W over the Mississippi River in Minneapolis, Minnesota, suddenly collapsed. This three-span bridge was designed in 1964 and the superstructure consisted of steel girder and concrete-slab approaches. This collapse killed 13 people and injured 145 others. Approximately 1,000 ft. of the 1,907 ft. long bridge fell into the water; it was one of the most recent catastrophic failures [74].

Figure 3-6: Structure of the I-35W Bridge over the Mississippi River in Minneapolis

(Source: National Transportation Saftey Board (NTSB) 2008) [220]

On the right side of Figure 3-6, the main structural components of the bridge are illustrated and on the left side a gusset plate which had retained the truss members of the bridge are highlighted. Traffic load was carried by a concrete deck resting on steel beams. These steel beams were supported by steel main trusses under it, and all of the loads were transferred to the ground through concrete piers [74].

The design of the bridge was flawless in all aspects except for the gusset plate. Although the bridge's truss-cell structure was appropriately designed, the design of the gusset plate was inadequate for effectively distributing live and dead loads. Figure 3-7 shows a gusset plate after the failure. It was concluded that the capacity of the gusset plates were inadequate to transfer the loads from beams to trusses [74].

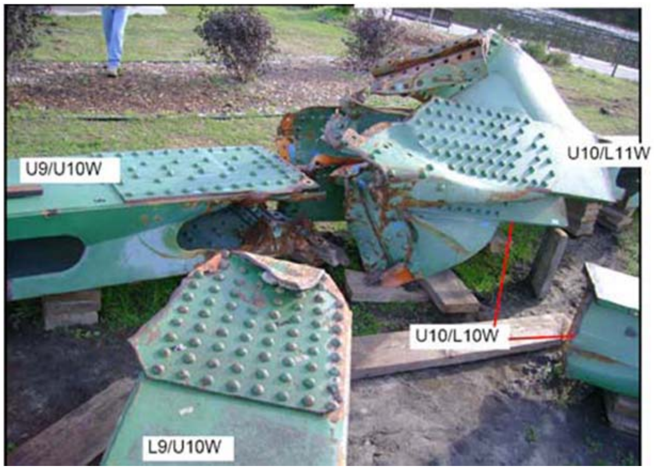


Figure 3-7 Gusset Plate of I-35W Bridge After Failure

(Source: National Transportation Saftey Board 2008) [220]

In 2007, after the failure of this eight-lane highway bridge caused by inadequate load capacity of gusset plates, the National Transportation Safety Board (NTSB) made recommendations to the Federal Highway Administration (FHWA) and American Association of State Highway and Transportation Officials (AASHTO) to carry out quality control in the design and construction phase of building a bridge. The NTSB investigation blamed Federal and State transportation officials for giving inadequate attention to the design of the gusset plates and other elements [105].

3.1.2 Lack of Maintenance

Inadequate inspection of bridges is one of the common causes of bridge failures, or sometimes it can make the situation worse and follow a bridge to collapse. A bridge designer always assumes appropriate maintenance in estimating the life of the designed bridge. Thus, during construction, the vital elements should be identified and made easily accessible for future inspections. Rusted parts must be replaced, drainage areas cleared, new coats of paint applied and reinforcements added if traffic levels have increased [4].

Case Study: Partial collapse of the Concorde Overpass in 2006

At 12:30 p.m. on September 30, 2006, the Concorde overpass in Laval, Quebec, Canada collapsed. In this collapse, three eastbound lanes and a pedestrian walkway of the bridge, which were made of pre-stressed box girder, fell down as seen in Figure 3-8. The failure was due to shear failure in one of the abutments. The young and modern overpass was constructed in 1970 with a life span of 70 years [188].

Figure 3-8: Concorde Overpass Partial Collapse

(Source: Johnson 2007) [122]

Routine inspections (in 1997, 1998, 2000, 2001, 2003 and 2004) and general inspections (in 1995, 1999 and 2002) were performed. These inspections essentially led to the following findings [122]:

- **Inspections, maintenance and repairs made before 1985**
    - Little information was available regarding the inspections made before 1985.
- **Inspections, maintenance and repairs made from 1985 to 1991**
    - Still in good condition, but there are signs of deterioration.
- **Inspections, maintenance and repairs made in 1992**
    - Replace the expansion joints as part of a larger repair program that also included the repair of concrete surfaces and the replacement of asphalt
- **Inspections, maintenance and repairs made From 1993 to 2004**
    - Since 1995, all reports mention the expansion joints continue to leak. In 1997, their replacement is considered.
    - In 1995, the slab received a rating of 4, which would have called for an assessment of the slab no later than 1999.
    - The first explicit mention of cracks was in 1997.
    - The repairs made in 1992 appear to be of dubious quality and in 2002, all loose concrete pieces were removed. In 2002, the general rating of the overpass was lowered from “good” to “acceptable.”
- **Inspections, maintenance and repairs in 2004**
    - The special inspection of 2004 does not fulfill the requirements set out in manuals and the report.
    - This inspection should have led to a condition evaluation of the structure including an evaluation of the load-carrying capacity and an evaluation of the condition of the materials. It is likely that the nature of the problems of the Concorde overpass would have been detected.
- **Inspections, maintenance and repairs between 2004 and 2006**
    - A new summary inspection took place in October 2004. It essentially reported the same observations noted on previous inspections. The general condition of the overpass was rated as “good.”
    - The last inspection performed on the bridge before its collapse was conducted in 2005. The rating for the box girders was lowered to 3 (extremities).
    - The main intervention carried out on the bridge between 2004 and 2006 consisted of removing loose fragments of concrete (safety improvement) under the superstructure. Work was performed on September 15, 2005.

Reviewing the inspection descriptions, which had been done during the 20 years before bridge collapse, reveals that the collapse could have been avoided if more rehabilitation was done. The collapse of this bridge resulted in a lot of attention to the maintenance and inspection of bridges during their service life.

3.1.3 Deficiency in Construction

A surprising number of bridges collapsed as they were being built. It might be thought that these types of collapses are not as serious because no one was driving on the bridge at the time of the collapse. Unfortunately, some of the deadliest bridge collapses in history have occurred during the bridge's construction. The lives of many workers are in danger during the construction stages of a bridge, while during the service life, only a few vehicles on it might be damaged. In this study, 38 bridges out of a total of 1,062 failed because of deficiency in construction. Although some bridges may not collapse during construction, they are doomed to collapse in service life because of a deficiency in construction. Figure 3-9(a) shows that 21% of the bridges failed during their service life due to deficiency in construction. Figure 3-9(b) shows the material of the bridges that failed because of faulty details in construction. Steel and concrete comprised of 92 % while only 8 % of the failed bridges were made of other materials. Of the 92 % class, steel bridges accounted for 40 % and concrete bridges accounted for 52 %. Interestingly, within the type of collapse category, partial collapses are more dominant (65%) in comparison to total collapses at 32%. Figure 3-9(c) shows this distribution. Table 3-7 shows the number of failure of different time of failure due to deficiency in construction. Table 3-8 and Table 3-9 give the number of failures for different material type and type of failures due to deficiency in construction.

Table 3-7: Time of Failure due to Deficiency in Construction

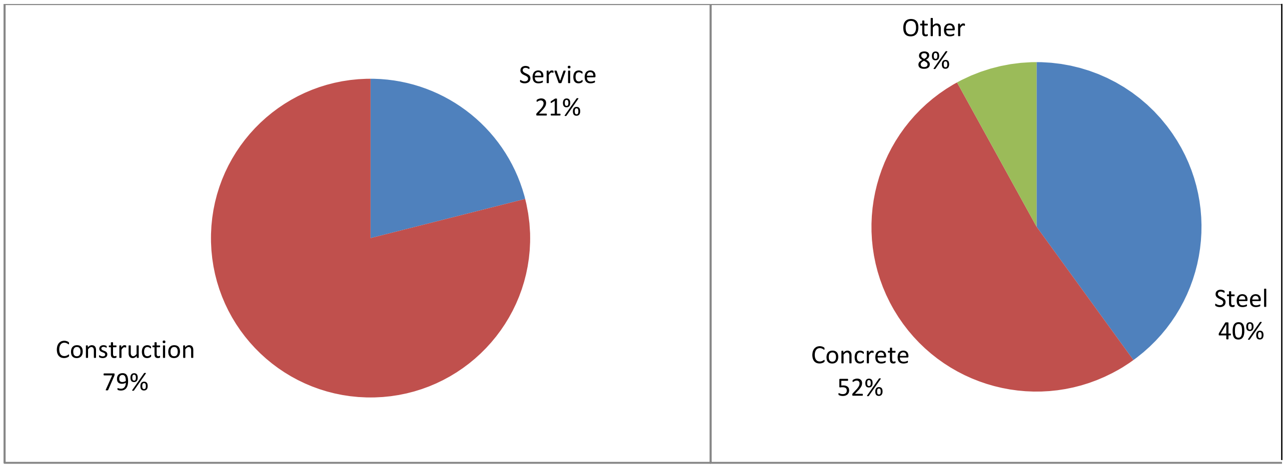
Time of Failure	Number of Failure
Service	8
Construction	30
Total	**38**

Table 3-8: Material Type in Bridges Failures due to Deficiency in Construction

Material	Number of Failures
Steel	10
Concrete	13
Other	4
Unknown	11
Total	**38**

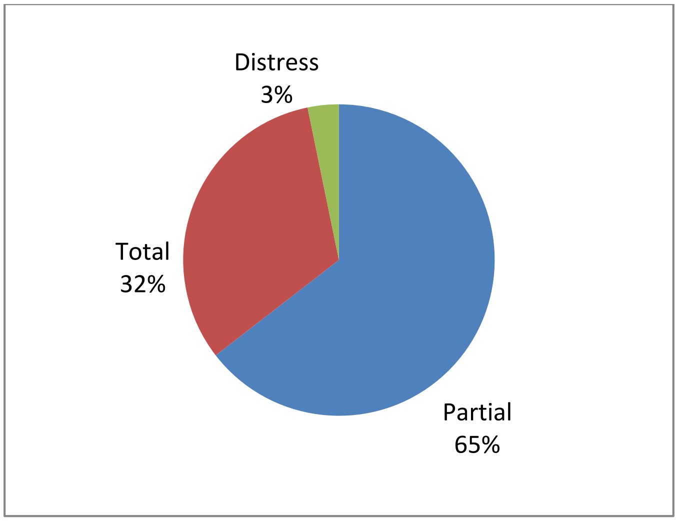
Table 3-9: Type of Failure of Bridges Failed due to Deficiency in Construction

Type of Failure	Number of Failure
Partial	20
Total	10
Distress	1
Unknown	7
Total	**38**



(a) Time of Bridge Failures due to Deficiency in Construction (38 failures)

(b) Material Type of the Bridges that Failed due to Deficiency in Construction (38 failures)



(c) Type of Failure due to Deficiency in Construction (38 failures)

Figure 3-9: Distribution of Time, Type, and Material of Failed Bridges due to Deficiency in Construction

Case Study: Collapse of the West Gate Bridge during Construction

The West Gate Bridge, located in Melbourne, Australia, was designed using two materials, the approach spans were constructed in reinforced concrete and the center part was a steel box-girder which was suspended by stay-cables. On October 15, 1970, the 112 m span collapsed suddenly during construction, resulting in of 35 fatalities. Figure 3-10 shows this bridge failure [2].

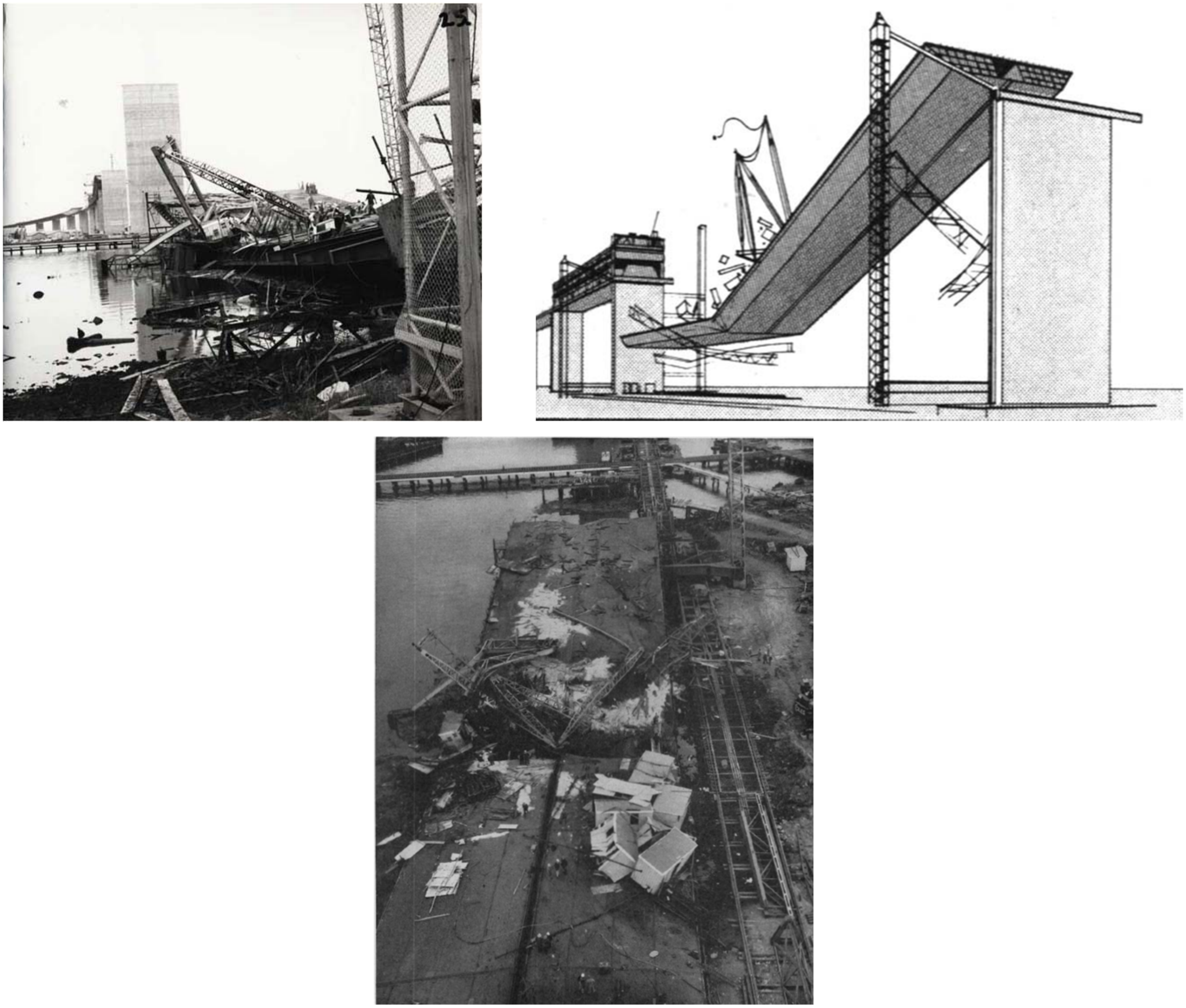


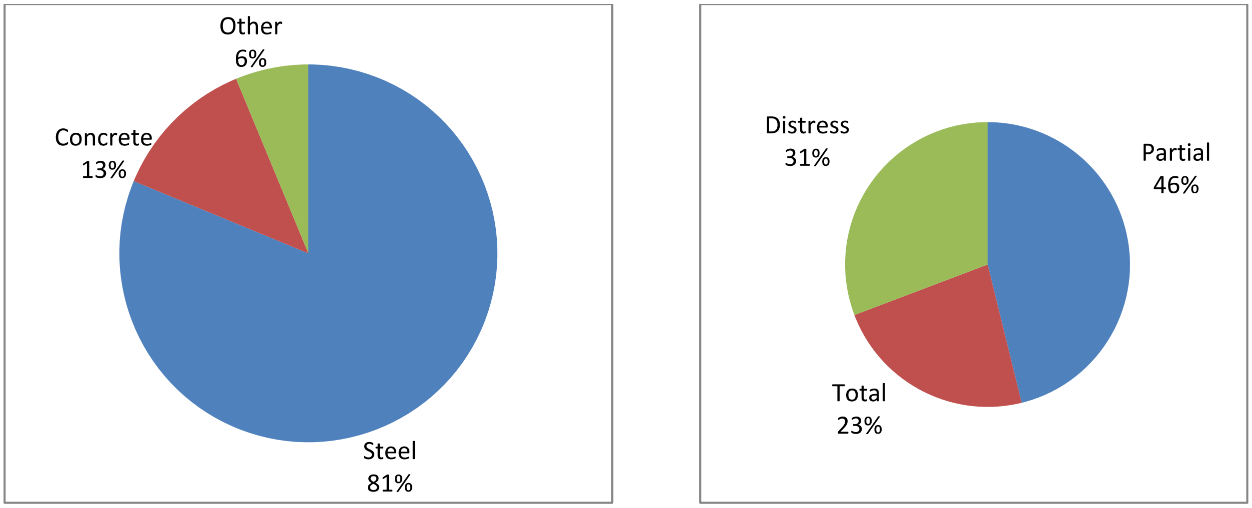
Figure 3-10: Collapse of the West Gate Bridge during Construction

(Source: Report of Royal Commission into the Failure of West Gate Bridge, by the West gate Royal Commission Act of 1970, No. 7989) [221]

Some faulty decisions by the contractor caused the bridge to collapse. The assembly method which was used in assembling the girder in two separate halves was uncommon. The load-carrying capacity was not calculated correctly. Also, the person in charge of inspection on site was not an experienced engineer.

3.1.4 Material Defect

Some bridge collapses are mysteries when they first happen. It isn't until a detailed investigation is completed that the true cause is revealed. At times, the simple failure of a small piece of the bridge caused the entire collapse. Sometimes, low-grade or faulty materials were used, rendering the entire bridge too weak to withstand the rigors of time. Before a new material is used in bridge construction, different structural and material tests should be done. All the information about the new material and its behavior should be examined and nothing should be left to chance to prevent brittle failures. Eighteen (18) of the bridges in the database of this project, had the cause of failure as material defect. As shown in Figure 3-11(a) steel bridges are more dominant in comparison to other type of material and this data would help the designer to consider more caution during the design of steel bridges. The interesting point in Figure 3-11(b) is related to the large amount of distress collapses (31%) because of the defect in material. For the whole database, the distress collapses were only 1 percent as seen in Figure 2-8. The high frequency of steel bridge failures can be attributed to their age became earliest bridge were made of steel. One other cause of steel bridge failures may be environmental degradation (corrosion, rusty, etc.) of steel bridges more than concrete bridges.



(a) Material Type in the Bridges that Failed due to Material Defect (18 failures)

(b) Type of Failure in Bridges that Failed due to Material Defect (18 failures)

Figure 3-11: Material Types and Failure Types due to Material Defect

Case Study: Distress of Sgt. Aubrey Cosens V.C. Memorial Bridge over the Montreal River at Latchford

This steel Sgt. Aubrey Cosens V.C. Memorial Bridge, located in Ontario, Canada, collapsed on January 14, 2003 at approximately 3:00 p.m. The distress failure happened while a tractor-trailer crossed the bridge; the concrete deck deflected approximately 2 meters at the northwest corner due to the failure of three hanger rods, as seen in Figure 3-12. The bridge was immediately closed to traffic [109].

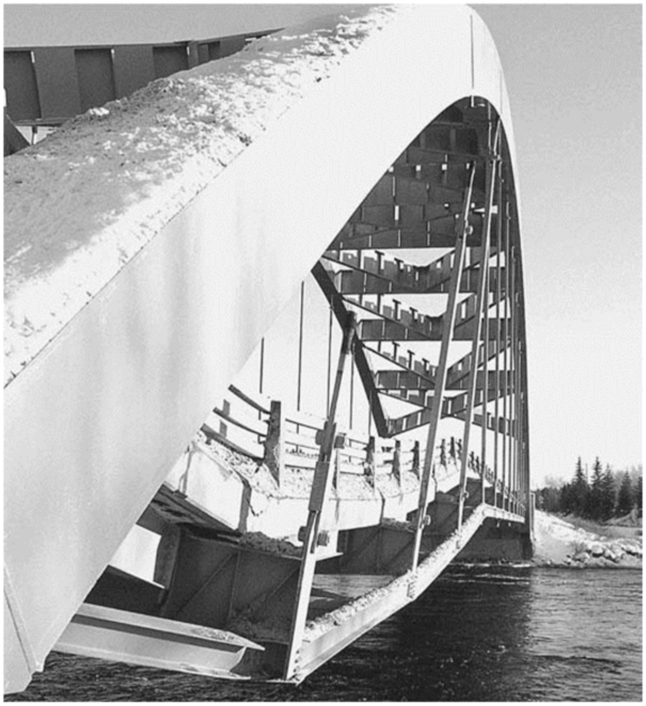


Figure 3-12: Distress of Sgt. Aubrey Cosens V.C. Memorial Bridge

(Source: Bagnariol 2003) [109]

Some fracture was initiated because of fatigue in the steel hanger rods. The design of these hangers was faulty and their capacity was not sufficient enough to bear the bending fatigue stress. In addition, during the construction of the bridge, some damage had happened to these hangers. Their critical portions were hidden during inspection. The most important cause of failure was the quality of the steel which was used in the bridge. It did not meet current standards for ductility in cold temperatures and chemical composition [109].

3.2 External Causes

The external causes that have caused bridge failures are listed in Table 3-10 in 10-year intervals. The top five external causes of bridge failures (1980-2012) are listed below:

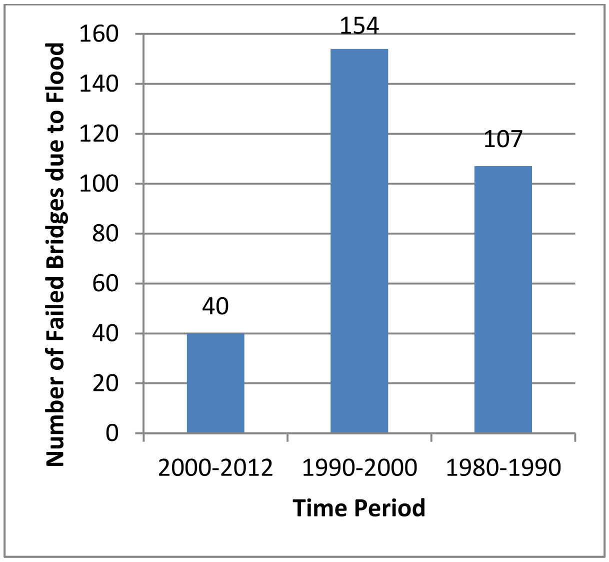
1. Flood
2. Scour

3. Collision
4. Overload
5. Environmental degradation

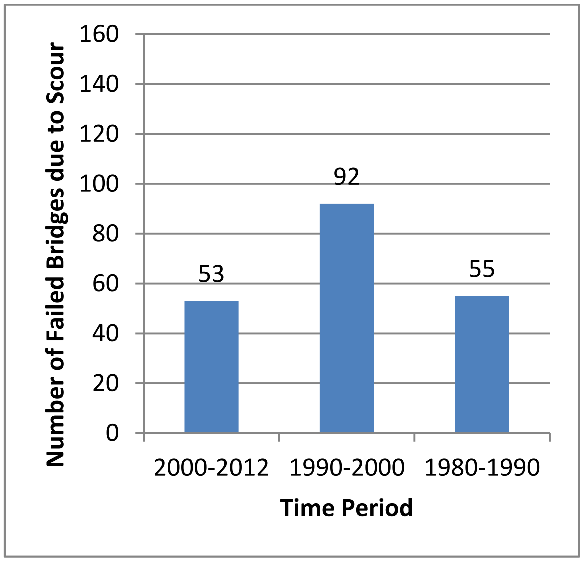
Table 3-10: Number of Bridges that Failed due to External Causes

External Cause of Failure	2000-2012	1990-2000	1980-1990	Total
Flood	40	154	107	301
Scour	53	92	55	200
Collision	51	55	57	163
Overload	37	31	67	135
Environmental Degradation	23	22	26	71
Fire	12	10	8	30
Earthquake	1	11	8	20
Wind	8	8	1	17

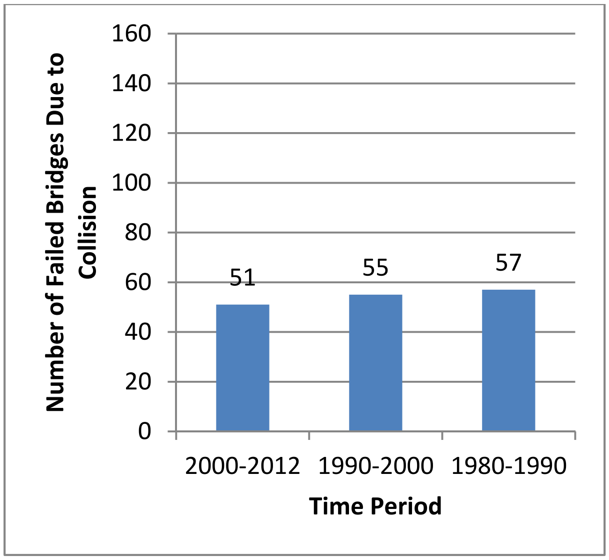
In Figure 3-13, the frequency of these top five causes is shown for separate decades.



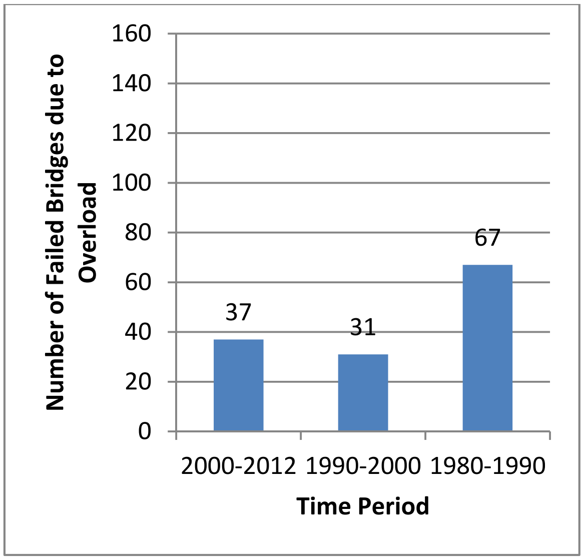
(a) Bridge Failures due to Flood



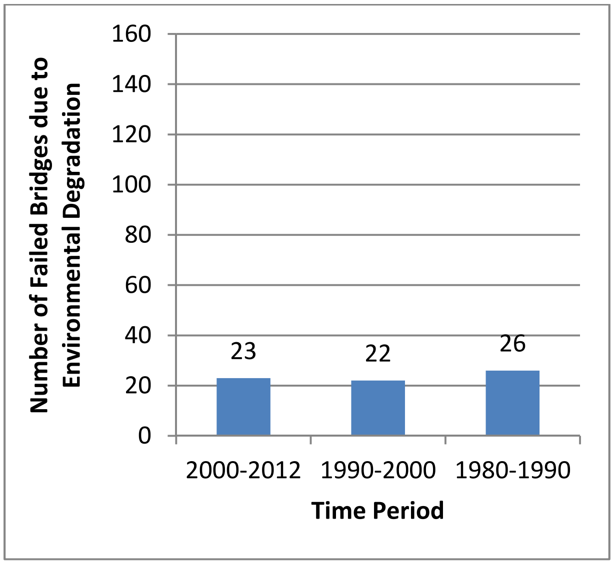
(b) Bridge Failures due to Scour



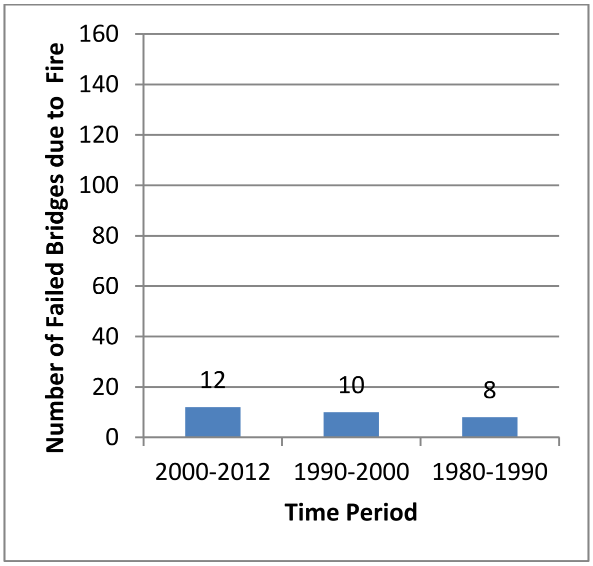
(c) Bridge Failures due to Collision



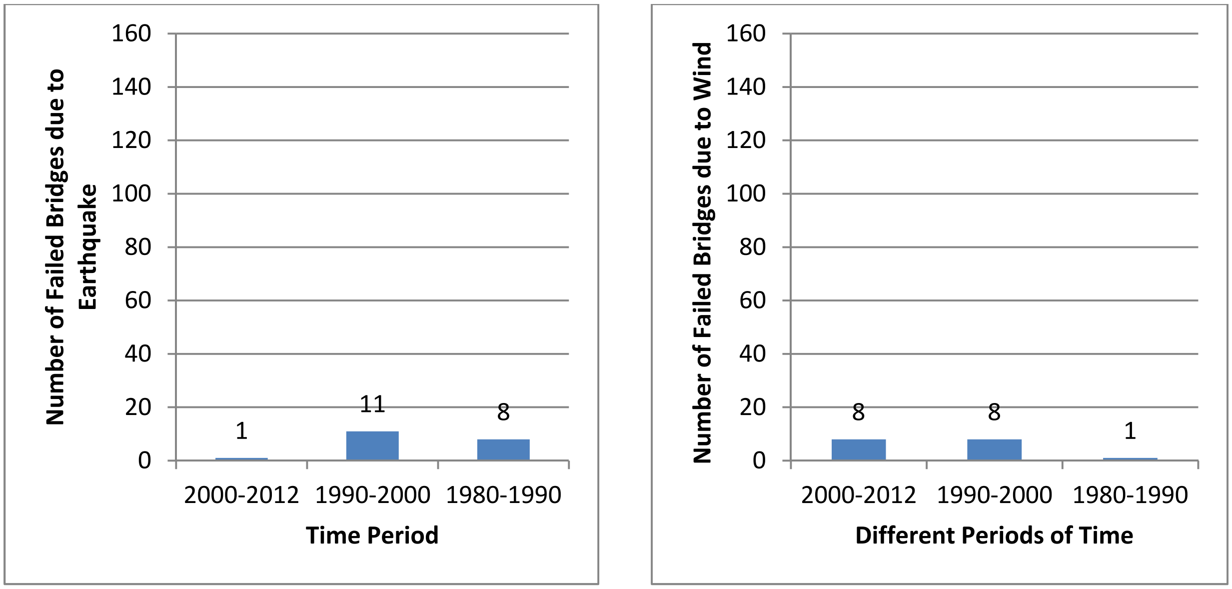
(d) Bridge Failures due to Overload



(e) Bridge Failures due to Environmental Degradation



(f) Bridge Failures due to Fire



(g) Bridge Failures due to Earthquake **(h) Bridge Failures due to Wind**

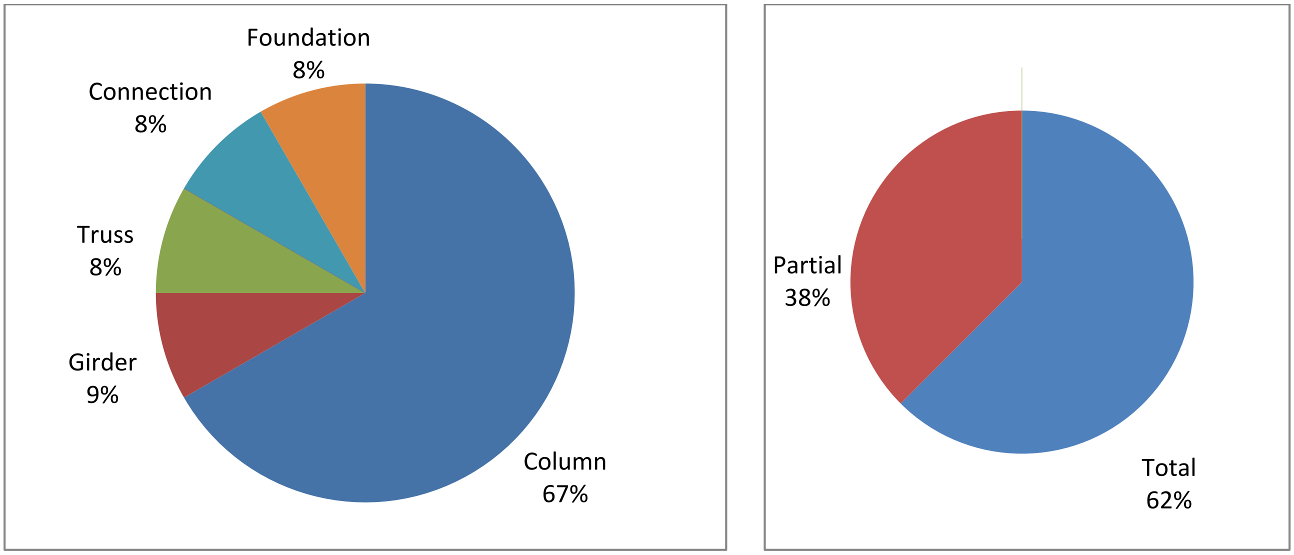
Figure 3-13: Frequency of Top Five External Causes of Bridge Failures in 10-year Intervals

Brief descriptions of each of the eight external causes are given below:

3.2.1 Earthquake

Bridges, like other structures, can be damaged during earthquakes. During the 1990s, some major earthquakes in Japan and the U.S. caused dozens of bridge structures to collapse, and the most visible sign of deficiency in seismic design codes was the collapse of bridges.

The bridge collapses due to earthquakes are categorized based on the structural elements (connection, girder, column, truss, foundation, and bearing) that failed. Figure 3-14(a) shows the failed bridge parts that needed more consideration during design. From the data collected in this report, it can be concluded that columns are the most vital part in the resistance of bridges against earthquake, 67 % of failures happened because of weak retrofitting of columns. Note that this distribution does not include all 20 bridge failures caused by earthquake, because some data was missing. In Figure 3-14(b), the portion of total failure at 62% is larger than that in the whole database (see Figure 2-8).



(a) Failure of Structural Elements due to Earthquake

(b) Types of Bridge Failures due to Earthquake

Figure 3-14: Distributions of the Failure Mode and Failure Type for Bridge Collapses due to Earthquake

After each catastrophic earthquake, design codes and specifications were revised to improve bridge design philosophies. For example in the 1994 Northridge and the 1995 Kobe (Hyogoken-Nanbu) earthquakes, the bridges were constructed according to design concepts of the 1970s (in accordance with pre-1971 and pre-I980 design methods), and suffered severe damage. Recently, a new concept of design based on the capacity design approach has made several developments in codes and specifications for the seismic design of bridges. The 1989 Loma Prieta, 1994 Northridge and 1995 Kobe earthquakes caused major damage to bridges in the U.S. and Japan; detailed research and further experiments after these failures have made major progress in different aspects such as near field ground motion, design of piers, design of foundations, and liquefaction and liquefaction-induced ground movement [83].

Near field ground motions developed in the Northridge and Kobe earthquakes were included in the 1996 Japanese and 1999 Caltrans design codes. The ductility design method and linear/nonlinear dynamic response analysis is now being used instead of the old and traditional seismic coefficient method. Japanese specifications provide a new solution for liquefaction and liquefaction-induced lateral ground movement and seismic retrofitting of over 2,700 reinforced concrete columns has been done to improve the ductility of bridges [83].

Revision in Seismic Design Codes and Specifications

In 1994, the European Pre-standard, which was part two of Bridges in the "*Eurocode 8*" design provisions for earthquake resistance of structures, was prepared. In 1995, the New Zealand authorities revised the "*Transit New Zealand Bridge Manual"* [26, 42]. In 1996, "*Design Specifications of Highway Bridges"* were fully revised in Japan [42]. In the United States, in two separate efforts, AASHTO and the Department of Transportation of the State of California (Caltrans) developed seismic design specifications for highway bridges and LRFD bridge design. The ATC-32 recommendation was published to improve Caltrans seismic design practice (ATC 1996). After that, the "*Seismic Design Methodology"* (Caltrans 1999a) and the "*Seismic Design Criteria*" (Caltrans 1999b) were issued by Caltrans [83]. In Taiwan, bridge design specifications have been revised three times since 1960. In 1960, the Ministry of Transportation and Communications (MOTC) prepared "*Highway Bridge Engineering Design Specifications*" based on AASHTO bridge design specifications issued in 1953. In 1987, it was reconsidered after the 1977 revision of AASHTO bridge design specifications. It was updated for the third time after the 1992 AASHTO specifications; unfortunately, the part that did not change very much was the seismic design section [101].

Case Study: Hanshin Expressway Collapse in 1996 Kobe Earthquake

The Hanshin expressway, an eighteen span bridge located in Japan, was designed based on 1964 design specifications with the allowable stress design approach. The bridge decks were simply supported and made of pre-stressed concrete to the length of 22 m. One meter diameter piles were constructed with a length of 10-15 m to support the piers [83].

Figure 3-15: Collapse of Hanshin Expressway in 1995 Kobe Earthquake

(Source: Shinozuka 1995) [222]

After the catastrophic failure, which can be seen in Figure 3-15, different investigations have been conducted to find the causes. It was disclosed that three major problems happened during the design of the bridge. First, the allowable shear stress in the code design was overestimated and the one in the code was less than 60% of the design stress. The second cause was the termination of the longitudinal bars at mid-height. The third cause was the insufficient amount of tie bars. The piers suffered strong ground motion and collapsed because of the insufficient amount of longitudinal bars and improper length of termination.

Interstate 5 (Golden State Freeway) Gavin Canyon Undercrossing Failure in Northridge Earthquake

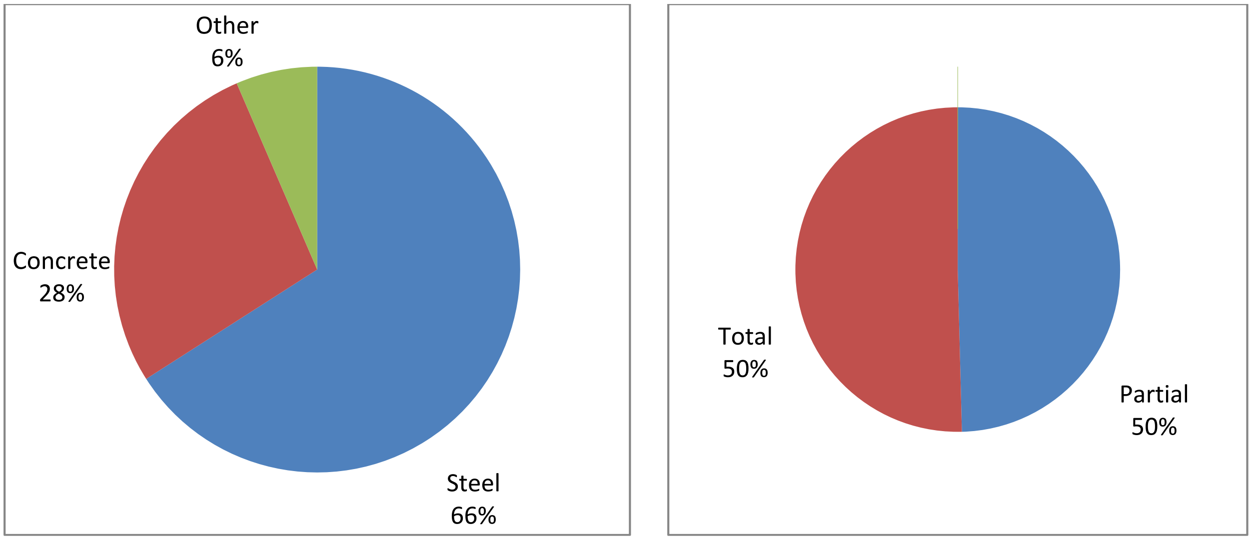
The Gavin Canyon Undercrossing had five spans with pre-stressed concrete box girders, which was designed in 1964 and constructed in Los Angeles, California in 1967. The structure consisted of two parallel bridges, with about a 66 degree skew alignment. With a structural hinge near each of the two-pier bents, the structure is simply-supported. This bridge had experienced the 1971 San Fernando earthquake without any visual damage except some retrofitting in 1974 for hinges. One of the features that showed the difference with the improvement of the codes is the seat length of the hinges. The seat length at the hinges was 200 mm, which by current design standards would be considered inadequate. This was probably the reason for the failure of three of the four end spans of the bridge as seen in Figure 3-16. Another important cause of the failure was the skewed alignment in conjunction with the tall and flexible piers of the two center bents of the bridge [85].

Figure 3-16: Collapsed Gavin Canyon Undercrossing

(Source: Buckle 1994) [223]

3.2.2 Scour

Scour is defined as the erosion or removal of stream bed or bank material from bridge foundations due to flowing water. To minimize future bridge scour damage and ensure public safety requires developing and implementing improved procedures for designing bridges and inspecting them for scour. Every bridge over water should be assessed as to its vulnerability to scour in order to determine the prudent measures to be taken for that bridge as well as the entire inventory [4]. In this study, 200 bridge collapses happened because of scour. As seen in Figure 3-17(a) steel bridges are more vulnerable to scour in comparison to other materials. In Figure 3-17(b) the percentage of partial and total collapse is charted and it can be concluded that partial collapse and total collapse are equally distributed in bridge failures due to scour.



(a) Material Type of the Failed Bridges due to Scour (200 failures)

(b) Type of Failure due to Scour (200 failures)

Figure 3-17: Material Types and Failure Types for the Bridges Collapse due to Scour

Case Study: Failure of the Houfeng Bridge because of Scour in 2008

The Houfeng Bridge over the Da-Chia River in central Taiwan collapsed in 2008. This bridge was made of concrete and partially collapsed because of scour, although some other causes also initiated this failure.

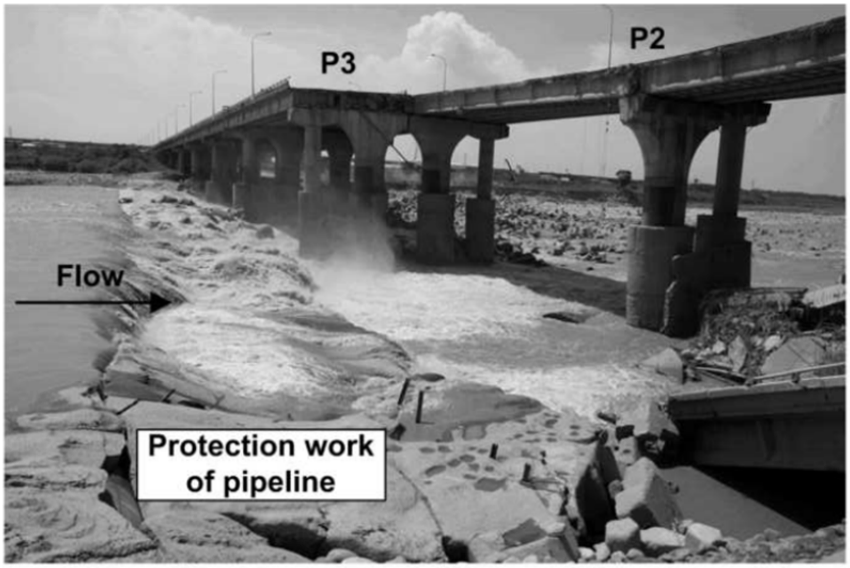


Figure 3-18: Partial Collapse of Houfeng Bridge due to Scour
(Source: Hong 2011) [78]

The major events that occurred during the life span of the bridge are listed below:

- In 1994, a water supply pipeline was constructed at a depth of 7 m beneath the surface.
- In 1999, the Chi-Chi earthquake occurred.
- In 2005, the water supply pipeline was exposed due to flood.
- In April 2008, three steel-fence type grade-control structures, located about 80 m downstream of the bridge, were constructed.

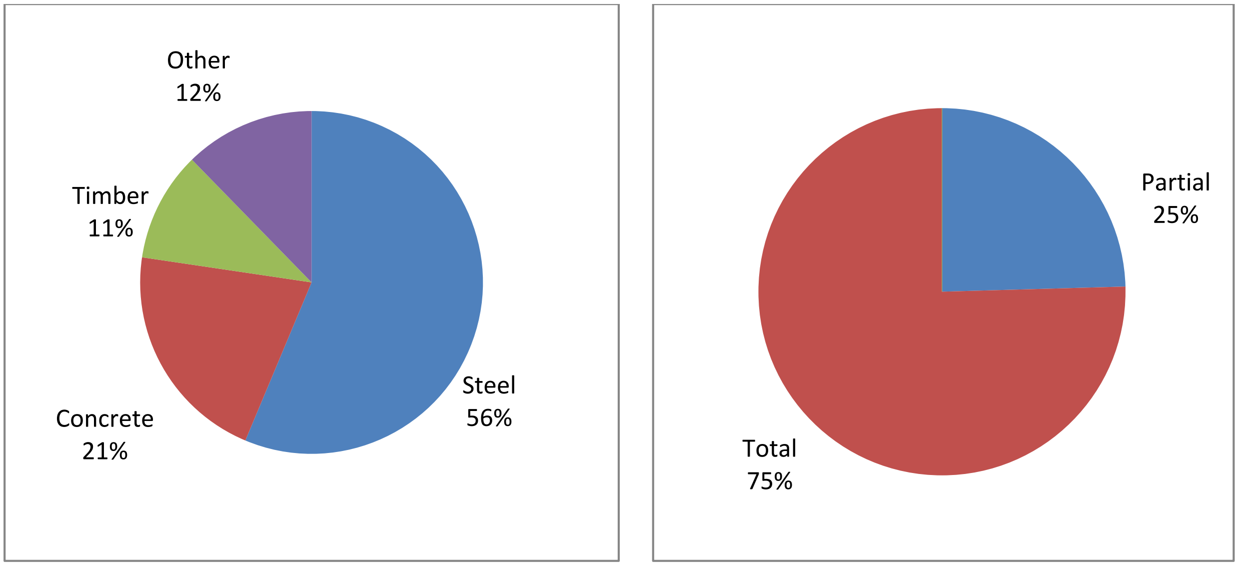
- In July 2008, foundations of piers 2 and 3 of the bridge were severely exposed during a flood event.
- In September 2008, officers started to block the collapse of pier 2 after blockade of one end of the bridge.

After a comprehensive investigation, it was declared that the direct cause of failure was scour. There were other causes which exacerbated the situation. Impinging jet scour generated by a concrete encased pipeline (Figure 3-18), a previous flood which happened two months before failure, and the long-term general scour caused by an earthquake played a significant role in this failure [78].

3.2.3 Flood

Flood can collapse a bridge in a few different ways. The common cause of bridge failures due to flood is by gradual wearing away of the earth and soil around the piers of the bridge. In this way, the failure force of water increases and finally when the capacity of bridges has been reduced, the bridge collapses. Flood also can smash bridges by trees or cars that are picked by the flow before reaching the bridge. This impact might destroy the bridge immediately or might make it vulnerable to other causes of failure [99].

In this study, 301 bridges out of 1,062 failed due to flood. Figure 3-19(a) shows that steel bridges at 56% are the most vulnerable to flood while the second place is for concrete bridges at 21%. In this class, the number of timber bridge failures at 11%, which is large in comparison to other causes of failures. As seen in Figure 3-19(b), most of the bridges that failed due to flood, totally collapsed (75%), which is the same as other external causes of failure.



(a) Material Type of the Bridges that Failed due to Floods (301 failures)

(b) Type of Failure due to Floods (301 failures)

Figure 3-19: Material Types and Failure Types in Bridge Collapses due to Floods

Case Study: Failure of Turag-Bhakurta Bridge due to Flood in Bangladesh

The 67 m long Turag-Bhakurta Bridge with a width of 3.70 m was constructed of concrete in 1994. In 1995 there was a flood in Bangladesh which did not hit the bridge, but caused some settlement that impacted bridge. Some rehabilitation was done to the bridge, but in 1998, it was totally washed away by flood as seen in Figure 3-20.

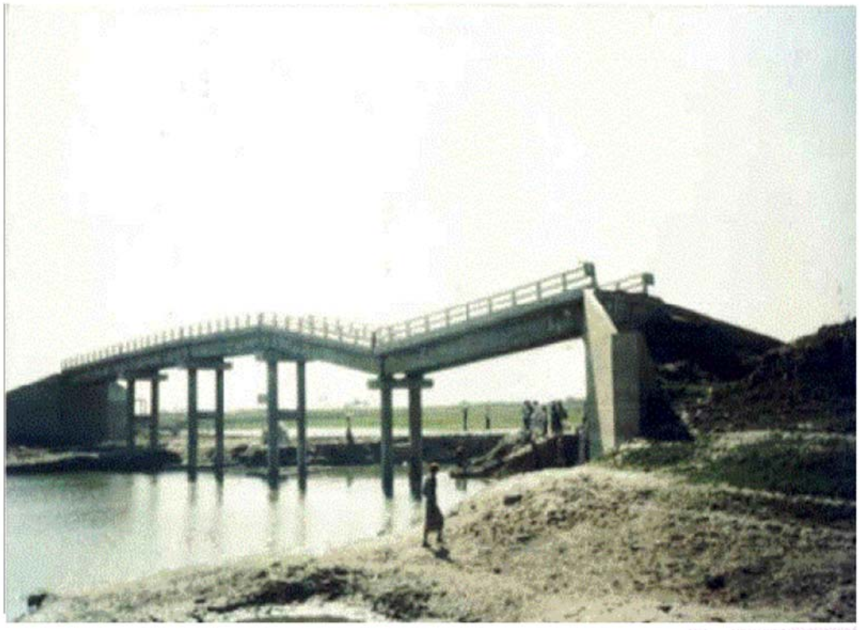


Figure 3-20: Failure of Turag-Bhakurta Bridge

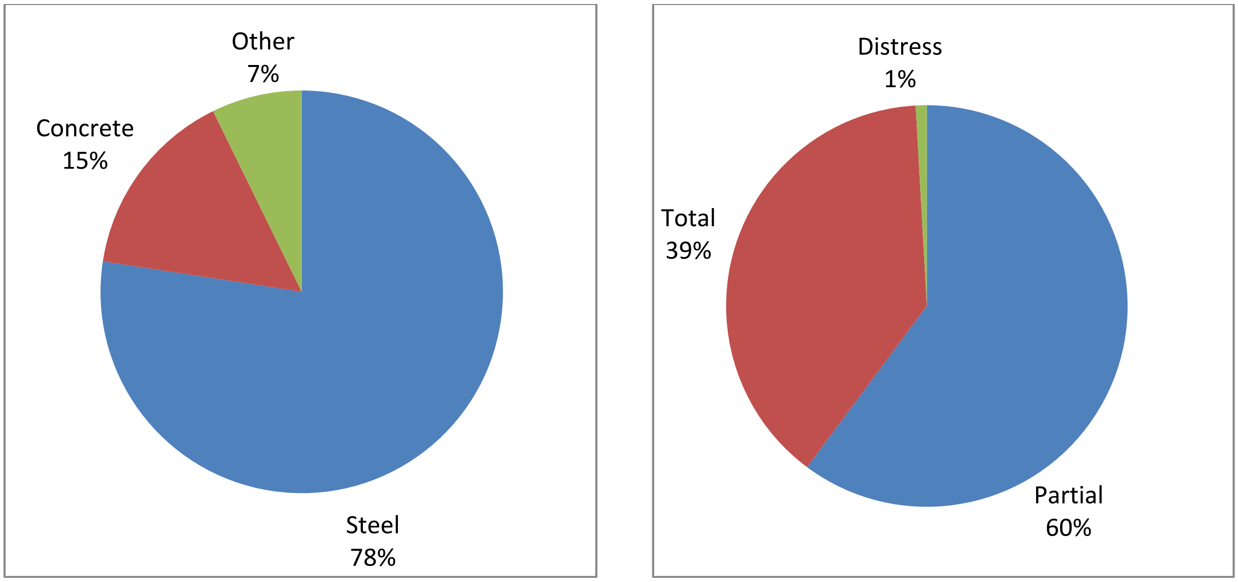
(Source: Bala 2005) [54]

Providing information on hydrology and hydraulics of waterways to the bridge designer might be helpful to avoid bridge failures. It may even be more useful than strict codes to avoid erection of flood-resistance measures. The most important factors leading to this type of disaster are summarized as:

- Lack of hydrological data upon which to base estimates of the magnitude of floods for design purposes.
- Ignorance of the hydraulics of flow in alluvial rivers and flow through bridge waterways and around bridge piers.
- Lack of reliable methods for estimating scour at bridge piers.
- Inability to predict the occurrence of impact and accumulation of debris against the bridge structure.

3.2.4 Collision

This class of failure mostly happens due to the collision of ships and bridges, but other types of failure such as collision of train or vehicle can be categorized as this kind of failure. Ships are moving slow while passing a bridge in comparison to trains or vehicles, but the problem is the huge mass of ships. Even a small contact between ships and bridges can cause a bridge to collapse. Figure 3-21(a) shows that steel bridges have included 78 % of failures due to collision. Partial collapse is more common in this class of bridge failures, as seen in Figure 3-21(b).



(a) Material Type of the Bridges that Failed due to Collisions (163 failures)

(b) Type of Failure due to Collisions (163 failures)

Figure 3-21: Material Types and Failure Types in Bridge Collapses because of Collision

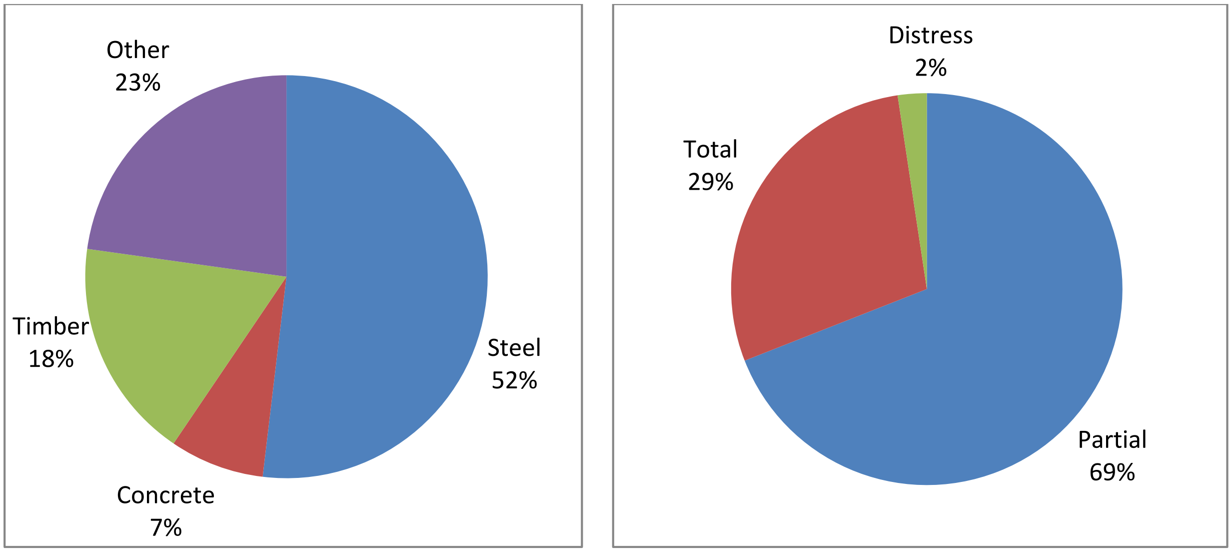
Case Study: Failure of the Tasman Bridge

The Tasman Bridge was constructed in Hobart, Tasmania in 1965. The bridge was made of concrete and opened to two lanes of traffic. In 1975, a bulk ore carrier ship struck the bridge and 3 spans collapsed, killing 12 people.

Human error such as misunderstanding between pilot and helmsman, and inattention can cause huge accidents that result in the loss of many lives. Ship officers should always put two trained and responsible professionals at the helm before approaching a bridge; recently developed directions were provided to avoid this kind of failure.

3.2.5 Environmental Degradation

The materials used in bridges are vulnerable to environmental degradation. In steel bridges, the primary metal used is iron and many problems can happen when this metal is in the environment. Corrosion and rusting are two major problems, known as "rust smacking," which may weaken the bridges' capacity whatever it feeds off of, appearing to bubble up the material. Structural elements of the bridge that contain enough rust can make the bridge completely or partially collapse as seen in Figure 3-22(b). In reinforced concrete bridges, corrosion and rust can cause problems because of the steel encased in the concrete. Bridges with other materials are also vulnerable to environmental degradation. In Figure 3-22(a), the number of timber bridges vulnerable to environmental degradation is 18%. In this study, 71 out of 1,062 bridges collapsed because of environmental degradation.



(a) Material Type of the Failed Bridges due to Environmental Degradation (71 failures)

(b) Type of Failure due to Environmental Degradation (71 failures)

Figure 3-22: Material Types and Failure Types of the Bridge Collapses because of Environmental Degradation

Collapse of the Silver Bridge over the Ohio River

In 1928, the Silver Bridge, with a 2,235 foot long span and two suspension lanes, was constructed to connect Gallipolis, Ohio and Henderson, West Virginia. The eyebars were used in this bridge as connections as an innovative design method. Environmental degradation of these eyebars was the direct cause of the collapse. This accident killed 46 people and the corrosion of these eyebars was the cause of the collapse [3].

The casting procedure of one of the eyebars had some deficiencies and after some years, stress corrosion and corrosion fatigue gradually made the bridge vulnerable, finally causing it to collapse.

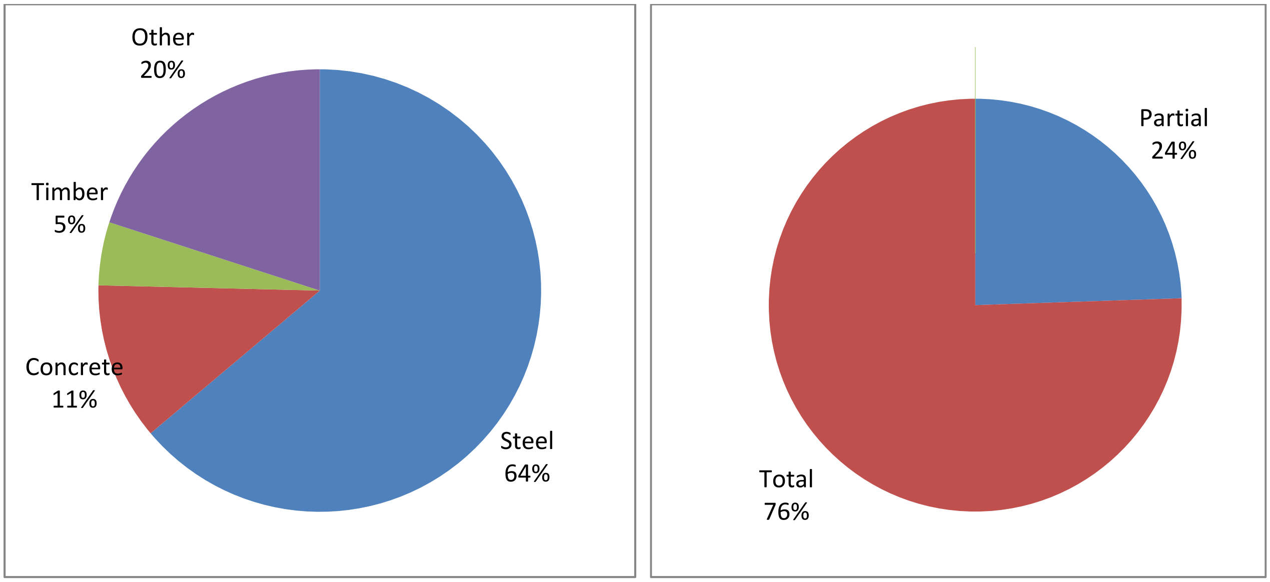
The Silver Bridge disaster is only one of the many bridge failures due to environmental degradation. It was also the cause of the 1983 Mianus River Bridge collapse in Connecticut and the 2003 Kinzua Bridge collapse in Pennsylvania.

3.2.6 Overload

Frequency and weight of trucks are two major causes of bridge failures, especially for older bridges because new trucks have more weight. Thus, for some bridges, detailed load limitations should be considered to avoid failure due to overload. Bridge overloads may contribute to an acceleration of fatigue damage in bridges.

Bridge design loads have been modified in order to have a safe limit for new bridges. Instability and overstresses might happen to certain bridges because of a large dynamic effect impact. Sometimes, even the width of new trucks can bring a bridge to collapse due to their inadequate design configuration [66]. In this study, 135 bridges failed because of overload. 76 % of the bridge failures caused by overload totally collapse as shown in Figure 3-23(b). In this class of failure, partial collapses are not as common as other classes of failures. Figure 3-23(a) shows that steel bridges are more vulnerable to failure due to overload at 64%. The percentage of timber bridges at 5% is interesting in this class.

The only calibrated design formula in the current AASHTO LRFD is the strength limit states I, i.e., the combination of dead load and live load. According to Nowak, a reasonable reliability index for bridge design is 3.5; that is, the probability of failure is equal to 0.000233. A rough possible calibration is: if it is assumed that there are approximately 600,000 bridges, and the probability of failure due to dead load and live load can be represented by overload, then the result is 135 / 600,000 = 0.000225, with the corresponding reliability index equal to 3.51. The agreement of these two results not only calibrates the rationality of the current AASHTO LRFD but also verifies the necessity of appropriate collection and understanding of damage information. This type of calibration can be extended to extreme event cases with different assumptions and conditions. For example, the assumption of denominator needs to be carefully selected when calculating the probability of failure due to the influence of an extreme event in a certain area, such as earthquake, flood, tsunami, etc.



(a) Material Type of Failed Bridges due to Overload (135 Failures)

(b) Type of Failure due to Overload (135 Failures)

Figure 3-23: Material Types and the Failure Types for Bridge Collapses because of Overload

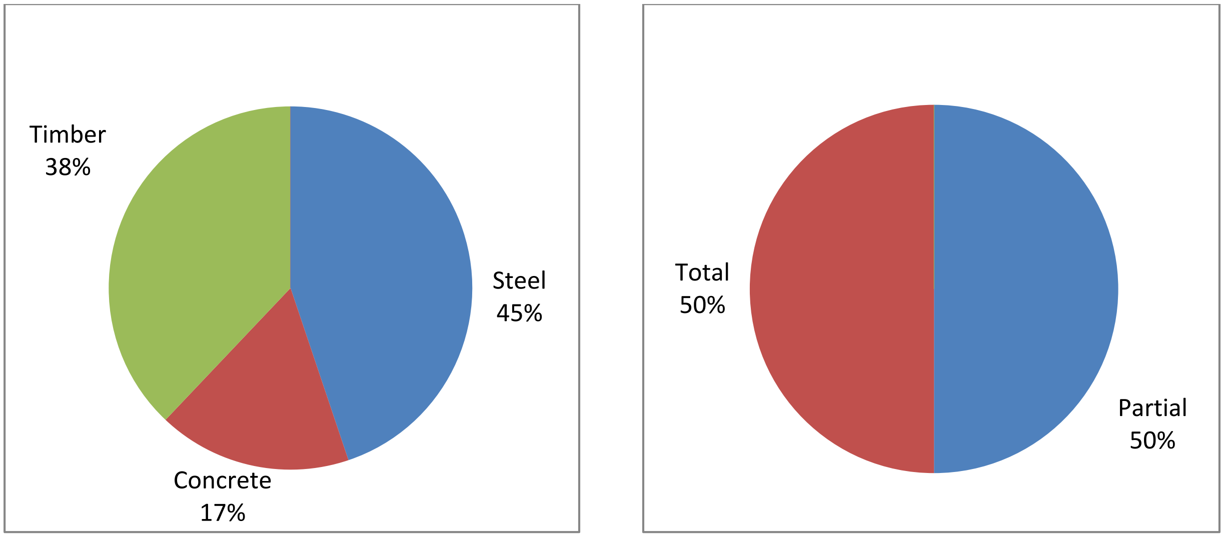
Case Study: Yangmingtan Bridge Collapse because of Overload

The Yangmingtan Bridge was constructed in Harbin, China in 2011 of concrete. This girder bridge had a length of 9.6 miles with eight lanes. In 2012, a nearly 330-foot-long section of a ramp of the bridge dropped 100 feet to the ground while some trucks were passing. Three people were killed and five others were injured because of this failure.

During the collapse of the bridge, four trucks were passing on it and after an investigation it was declared that the cause of the failure was overloaded trucks. The age of the bridge at the time of the failure was less than one year, so in this case the design loads probably should have conformed with the weight of the new trucks. Additionally, having four full trucks at the same time and even on the same lane made the bridge more vulnerable to collapse. In this case, some restriction on the number of trucks could have prevented the failure.

3.2.7 Fire

Wood and timber bridges are very vulnerable to fire and reducing the number of these types of bridges has resulted in a corresponding decrease of the numbers of bridge failures due to fire. Fire is one of the rarest causes of bridge failures. In fact, at one time it was much more common, when most bridges were made of wood. Train bridges were especially susceptible to fire, because of the sparks between steel rails and the steel wheels during winds and dry weather conditions. However, steel bridges, concrete bridges, and other types of bridges can be susceptible to failure by fire. The crash of a tanker carrying a large amount of a highly flammable substances, wildfires, or arson can bring a modern bridge down. It should be mentioned that even though fire might have started the failure, most of the time there is another cause of failure as well [189]. In this study, 30 bridges failed because of fire. The percentages of partial or total collapse are exactly the same, almost similar to the whole database. Figure 3-24(a) shows that timber bridge failures have a significant percentage in this category at 38%. Steel bridges were still the most vulnerable material at 45% in comparison to other material types.



(a) Material Type of the Failed Bridges due to Fire (30 Failures)

(b) Types of Failure due to Fire (30 Failures)

Figure 3-24: Material Types and Failure Types in the Bridge Collapses because of Fire

Case Study: Collapse of MacArthur Maze in Oakland, California

The two spans of the MacArthur Maze were constructed in 1930 and, after the Loma Prieta earthquake, these two spans were rehabilitated. This steel bridge was an elevated freeway in Oakland, California. On April 29, 2007, a fire was caused by a tanker truck that overturned on the bridge.

After several investigations, it was concluded that if the vulnerability of the exposed steel girders of the bridge was studied before and some prevention strategies such as a fire-protective material had been applied to the bridge, the collapse could have been avoided. This bridge was made out of steel and by using variety of technologies, this failure would not have occurred [20].

3.2.8 Winds, Windstorms, and Hurricanes

Hurricanes, tornados, and winter storms can ruin the total structure of bridges and these extreme hazard events might occur in any place and at any time. In 2003, an Office of Science and Technology Policy Report: *Assessing Federal Research and Development for Hazard Loss Reduction*, published an estimate of the total losses because of wind and hurricanes and reported that the damage was around $11.3 billion as shown in Table 3-11[59].

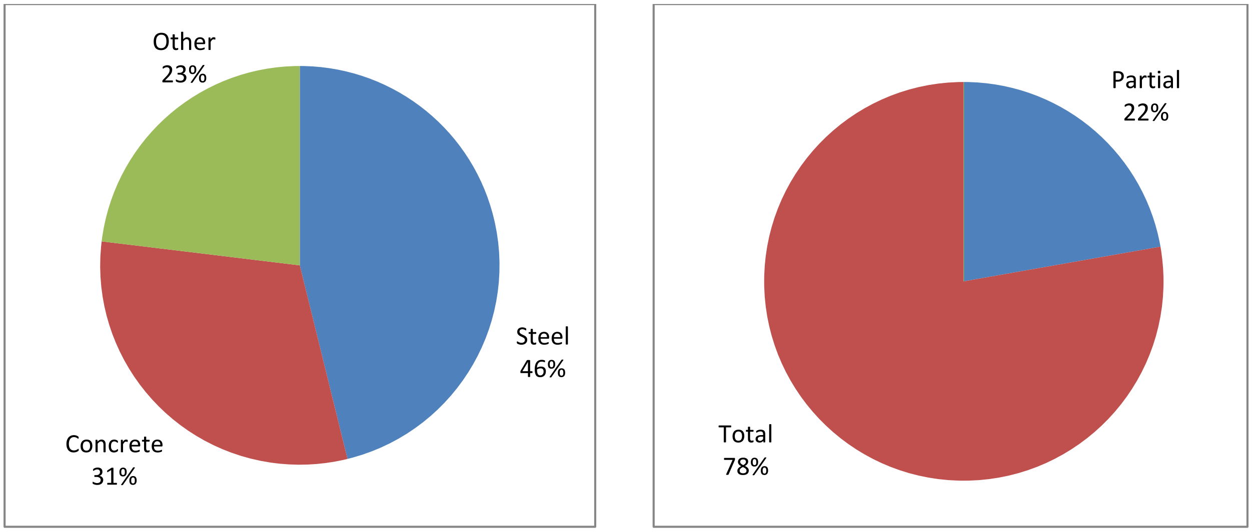
Table 3-11: Estimation of Annual Hazard Damage due to Extreme Events

Type of Hazard	Annual Hazard Damages ($ billions)
Hurricanes	5.0
Winter Storms	0.3
Tornadoes	1.0
Total Wind	6.3
Flood	3.0
Earthquakes	4.4

(Source: Meade and Abbott 2003) [224]

Vibrations in the whole bridge or in an element of the bridge such as beams, decks, columns, or trusses can be initiated because of wind. The Tacoma Narrows Bridge in Tacoma, WA, on November 7, 1940, is an example of this kind of failure [59].

In this study, 17 bridge failures because of wind were included, and in a separate effort, 29 bridge failures because of Hurricane Katrina in 2005 were collected. In Figure 3-25(b), the total collapse due to wind is dominant at 78% and makes a huge difference in comparison to the entire database.



(a) Material Types of the Bridges that Failed due to Extreme Wind (17 Failures)

(b) Types of Failure due to Extreme Wind (17 Failures)

Figure 3-25: Material Types and Failure Types in the Bridge Collapses because of Extreme Wind

Case Study: Collapse of the Interstate 10 Twin Bridge during Hurricane Katrina

The Interstate 10 Twin Bridge was one of the interesting collapses due to the Hurricane Katrina. This simply-supported concrete bridge was constructed in 1963, and collapsed during the hurricane as seen in Figure 3-26. Two nearby bridges survived the hazard but this bridge, by its collapse, made a challenging case for more investigation.

Figure 3-26: Spans of the Interstate 10 Twin Bridge were dropped off by Hurricane Katrina

(Source: O’Connor 2005) [225]

After the forensic studies, it was concluded that the problem with the bridge was its reduced capacity. It was mentioned that air was trapped under the bridge deck and because of that, the effective gravity load was decreased. Research to find the exact effect of the hurricane and wave action is still being conducted [62].

SECTION 4

SUMMARY

This report describes the bridge damage information collected by the authors, with emphasis given to the data sources and an explanation about how the collected information is documented. Preliminary statistical analyses were conducted to demonstrate some possible uses of the collected information on bridges in North America. For example, it is found that truss bridges are more vulnerable than other bridges, and therefore structural type should be used to prioritize the inspection and maintenance of bridges. A recent FHWA emphasis on "Fracture Critical" bridge failures coincides with this preliminary observation (See Figure 4-1).

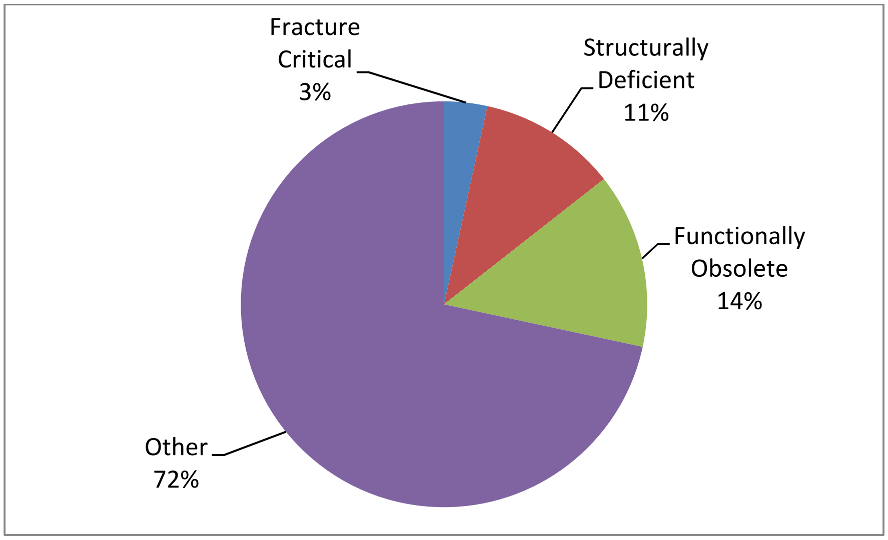


Figure 4-1: Bridge Statistics (December 2012)

(Source: FHWA 2012) [50]

On the other hand, the primary objective of this data collection is to establish load distribution patterns and to calculate bridge failure probabilities to further improve the reliability-based

LRFD bridge design specification. The information collected and presented in this report is not sufficient to achieve this primary objective.

Obtaining a more quantitative understanding of historical bridge failures is a key challenge in the development of bridge design specifications. It is worthwhile for researchers and engineers to study various aspects of current damage information, one bridge at a time, and carry out quantitative analyses on the causes of bridge failures to help establish structural reliability information of the bridges, as depicted in Figure 1-2. For example, a preliminary result of the collected information can be used for the calibration and development of the current AASHTO LRFD specification. A rough calculation on the probability of failure due to overload shows that there is good agreement between the analytical results from the current AASHTO LRFD and the actual historical data. This type of calibration can be extended to extreme event cases with different assumptions and conditions. For example, the assumption of denominator needs to be carefully selected when calculating the probability of failure due to an extreme event's influence in a certain area, such as earthquake, flood, tsunami, etc. In other words, the results of in-depth analyses on case studies due to different hazards can be utilized to identify the causes and definitions of bridge damage and failures, to further improve design principles, methodologies and eventually the specifications. This information collection effort at the national level should be continued in the future by FHWA or some other organization.

To continuously improve the data documentation and its contents, a more comprehensive electronic database on bridge damage and failures needs to be developed to be able to establish damage models and to conduct forensic studies to improve the AASHTO LRFD Extreme Event Design Limit State equations. Since 2009, MCEER researchers have been developing a beta version of an electronic database: *'Database of Damaged Bridges (DDB)'* [219]. The objective of this database is to provide sufficient quantitative information for structural and statistical analyses of bridge damage/collapses, to further provide fundamental knowledge for improving current design specifications from the viewpoint of engineering practice. This proposed DDB consists of four major components: hazard information, as-built structural design information, bridge damage information, and other information such as economic losses, injuries and fatalities. Figure 4-2 shows the structure of the DDB.

The information collected in this report provides significant sources for use in the development of principles and approaches of MH-LRFD. However, they serve as the "bridge damage information," which is only one part of an integral DDB. Moreover, the DDB needs to be improved by assembling reviews from experts and professionals. For instance, a national or international workshop should be convened to discuss topics such as establishing national or international standards of measurement of different hazards, developing a commonly understandable format, and discussing how to conduct data mining of past bridge failures.

With a continuously improved DDB, it will be possible to obtain adequate information to enhance load models, calibrate the probability of failure, determine the target reliability, identify the importance of different resistances, and eventually develop MH-LRFD limit states.

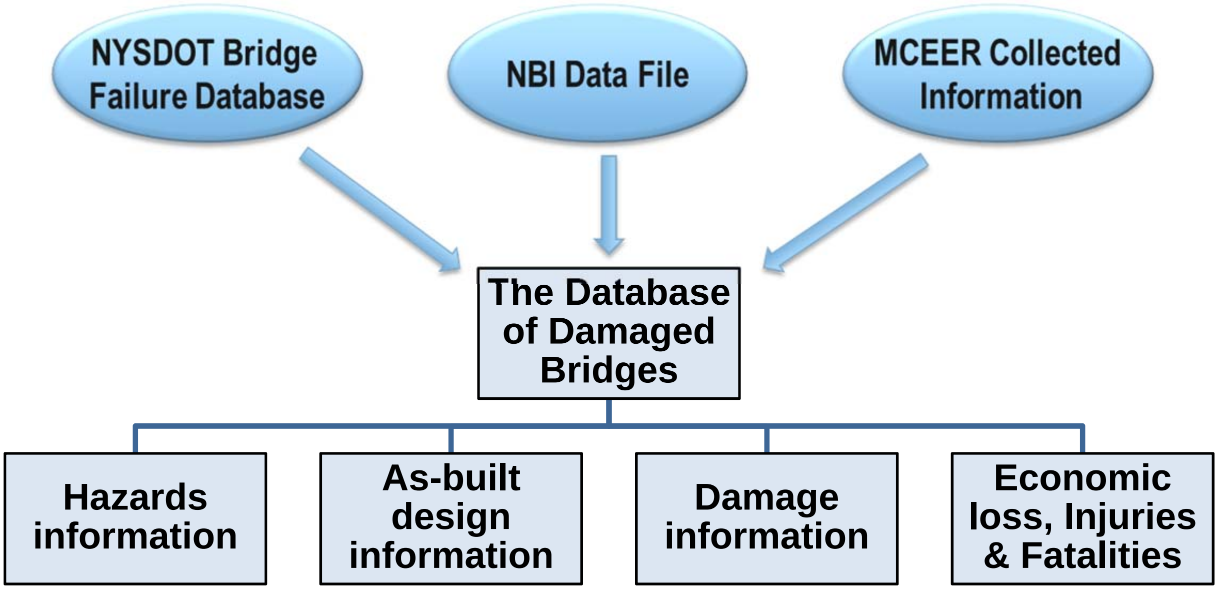


Figure 4-2: Proposed Structure of DDB

SECTION 5

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SECTION 6

TERMINOLOGY

Abutment

A retaining wall supporting the ends of a bridge.

American Association of State Highway and Transportation Officials (AASHTO)

AASHTO is a nonprofit, nonpartisan association representing highway and transportation departments.

Arch Bridge

A bridge whose main support structure is an arch.

Bascule Bridge

A bascule bridge features a movable span (leaf) that rotates on a horizontal hinged axis (trunnion) to raise one end vertically. A large counterweight is used to offset the weight of the raised leaf.

Bearing

A device at the ends of beams that is placed on top of a pier or abutment. The ends of the beam rest on the bearing.

Box Girder Bridge

A box girder bridge is a bridge where the main beams comprise girders in the shape of a hollow box. The box girder consists of prestressed concrete, structural steel, or a composite of steel and reinforced concrete.

Cable-Stayed Bridge

A variation of suspension bridge in which the tension members extend from one or more towers at varying angles to carry the deck.

Cascading failure

A failure in a bridge in which the failure of an element can trigger the failure of successive elements.

Cast-in-Place

Concrete poured within formwork on site to create a structural element in its final position.

Deck

The roadway portion of a bridge, including shoulders.

Distress

Some members of the bridge cannot bear the load and just by deformation show the need of rehabilitation while the bridge is still alive and usable.

External cause of failure

Directed to the demand of the bridge and consists of Scour, Flood, Earthquake, Fire, Collision, Wind, Overload, Settlement, and Environmental degradation of members.

Fatigue

Cause of structural deficiencies, usually due to repetitive loading over time.

Girder

A horizontal structure member supporting vertical loads by resisting bending. A girder is a larger beam, especially when made of multiple metal plates.

Gusset Plate

A metal plate used to unite multiple structural members of a truss.

Hanger

A tension member serving to suspend an attached member.

Highway bridges

Highway bridges are designed for heavy rolling loads of up to 0.8 mega newtons (80,000 tons of force), crowds of people, and other forces. The width of the driving part depends on the expected intensity and speed of the traffic and on the shape and span (usually 7–21 m) of the bridge; the sidewalks are at least 1 m wide.

Internal cause of failure

Directed to the capacity of the bridge and consists of: Faulty design, Error in Construction, Low Quality Materials, and Lack of Maintenance.

Partial Collapse

All or some of the primary members of a span or multiple spans have undergone severe deformation such that the lives of those traveling on or under the structure would be in danger.

Pier

A vertical structure that supports the ends of a multi-span superstructure at a location between abutments.

Roadway Bridges

Roadway bridges are designed for usual loads and people, and other forces. The width of the driving part depends on the expected intensity and speed of the traffic and on the shape and span of the bridge.

Skew

When the superstructure is not perpendicular to the substructure, a skew angle is created. The skew angle is the acute angle between the alignment of the superstructure and the alignment of the substructure.

Substructure

The substructure consists of all parts that support the superstructure. The main components are:

- Abutments
- Piers
- Footings
- Piling

Superstructure

The superstructure consists of the components that actually span the obstacle the bridge is intended to cross. It includes:

- Bridge deck,
- Structural members

Suspension Bridge

A bridge which carries its deck with many tension members attached to cables draped over tower piers.

Total Collapse

All primary members of a span or several spans have undergone severe deformation such that no travel lanes are passable.

Trussed Arch

A metal arch bridge that features a curved truss.

Appendix A - Documentation of Bridge Failures in the U.S.

The information of bridge damage and collapse are collected from different sources as mentioned in Chapter 2. These information are used to generate a spreadsheet with 56 entries, including:

❖ General Information of the Bridges

- Bridge number
- Name of bridge
- Reference (sources)
- Location
    - Country
    - State/Province
- Facility type
- Location of main structure (above/below/coincide with the deck line)

❖ Structural Information of the Bridges

- General structural information
    - Structure type of bridge
    - Detailed description
    - Material type
    - Support type
    - Other structural information
- Substructure information
    - Material, structural type and detailed description of Column
    - Material, structural type and detailed description of Connection
    - Material, structural type and detailed description of Abutment

    - Material, structural type and detailed description of Foundation
- Superstructure information
    - Material, structural type and detailed description of Girder
    - Material, structural type and detailed description of Connection
    - Material, structural type and detailed description of Deck
- Bridge Configurations
    - Number of Lanes
    - Number of Span
    - Length of Span
    - Length of maximum span
    - Deck Width
    - Column Height
    - Skew

❖ Failure Information of the Bridges

- History of Bridge
    - Year constructed
    - Year failed
    - Age
- Specification used for design basis
- Overall Failure Mode
    - Internal/External causes
    - Failure types
    - Description
- Detailed Failure Information of Column
    - Location of the failed components
    - Specific Location of failure on the failed components

  - Cause
  - Description
- Detailed Failure Information of Girder
  - Location of the failed components
  - Specific Location of failure on the failed components
  - Cause
  - Description
- Detailed Failure Information of Truss
  - Location of the failed components
  - Specific Location of failure on the failed components
  - Cause
  - Description
- Detailed Failure Information of Bearing
  - Location of the failed components
  - Specific Location of failure on the failed components
  - Cause
  - Description
- Detailed Failure Information of Connection
  - Location of the failed components
  - Specific Location of failure on the failed components
  - Cause
  - Description
- Detailed Failure Information of Foundation
  - Location of the failed components
  - Specific Location of failure on the failed components
  - Cause
  - Description
- Detailed Failure Information of Other components
  - Location of the failed components

    - Specific Location of failure on the failed components
    - Cause
    - Description
- Time of Failure (Service/Construction)
- Type of collapse (Total/Partial/Distress)
- Prevention suggestions

These collected information can provide the data source for the Database of Damaged Bridges (DDB) developed by MCEER researchers [219]. The general information and structural information of the bridges can serve as the input of the as-built design information in DDB while the failure information can serve as the input of damage information. With more sophisticated and elaborate technology of DDB, the in-depth structural and statistical analysis on the causes of bridge failure can be conducted more conveniently. The results are expected to be more realistic so they will provide a better basis for improvement of bridge design specifications.

A link to download the spreadsheet is as follows:

http://mceer.buffalo.edu/publications/reports/13-0008/default.asp

MCEER Technical Reports

MCEER publishes technical reports on a variety of subjects written by authors funded through MCEER. These reports are available from both MCEER Publications and the National Technical Information Service (NTIS). Requests for reports should be directed to MCEER Publications, MCEER, University at Buffalo, State University of New York, 133A Ketter Hall, Buffalo, New York 14260. Reports can also be requested through NTIS, P.O. Box 1425, Springfield, Virginia 22151. NTIS accession numbers are shown in parenthesis, if available.

NCEER-87-0001 "First-Year Program in Research, Education and Technology Transfer," 3/5/87, (PB88-134275, A04, MF-A01).

NCEER-87-0002 "Experimental Evaluation of Instantaneous Optimal Algorithms for Structural Control," by R.C. Lin, T.T. Soong and A.M. Reinhorn, 4/20/87, (PB88-134341, A04, MF-A01).

NCEER-87-0003 "Experimentation Using the Earthquake Simulation Facilities at University at Buffalo," by A.M. Reinhorn and R.L. Ketter, not available.

NCEER-87-0004 "The System Characteristics and Performance of a Shaking Table," by J.S. Hwang, K.C. Chang and G.C. Lee, 6/1/87, (PB88-134259, A03, MF-A01). This report is available only through NTIS (see address given above).

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