Bridge Failures: Causes, Analysis & Lessons Learned

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INTRODUCTION

Bridge failure has dramatic consequences in every nation's transportation system. In addition to casualties and loss of lives, the disruption in the service results in tremendously adverse effects on economic growth. For example, the failure of the Quebec Bridge in 1907 caused 75 deaths during construction, and the failure of the Silver Bridge in 1967 killed 46 people during service. In 2007, Tuojiang Bridge catastrophically collapsed during construction, resulting in 64 deaths and 22 injuries as well as a direct economic loss of about 39.747 million yuan. In 2018, the Italian Morandi's Polcevera Viaduct collapsed during service, resulting in 43 deaths and 9 injuries as well as a direct economic loss of about 100 million yuan. During the period between 1980 and 2012, a total of 1,062 bridge failures were reported in the United States, causing huge losses to the nation.

Principal causes of bridges failure can be divided into internal causes and external causes or natural factors and human factors. Design error, construction mistakes, hydraulic, collision, and overload are the top 5 leading causes of bridge failures, resulting in more than 70% of the bridge failures.

CAUSE OF FAILURE OF BRIDGE

Causes Classification

Bridge failure causes can be classified into principal causes and specific causes. Table 1 lists bridge failure causes. Principal causes can be divided into internal causes and external causes or natural factors and human factors. Internal causes, which include design error, construction mistakes, lack of maintenance, material defect, etc., usually require detailed failure investigations, such as material test, an inspection of design, construction, and maintenance documents, structural calculation, etc.

External causes include natural disasters such as earthquake, flood, fire, and wind, as well as extreme loads such as collision and overload. And this kind of cause can be roughly determined through the accident scene investigation. Natural factors are mainly natural disasters, including earthquake, flood, wind, etc., which are not easy to control and prevent. Human factors are mainly associated with human cognitive limitations, carelessness, mismanagement, etc., containing design error, construction mistake, lack of maintenance, material defect, collision, overload, etc.

The proportion of bridge failures due to internal causes has been decreasing with the development of bridge design, manufacturing, construction, and maintenance technology, as well as the development of the economy. In addition, natural disasters, collision, and overload of external causes contributed to a larger proportion of bridge failures.

Principal causes and specific causes	Top 5 leading causes and their proportion	Total proportion of the top 5 leading causes (%)	Total proportion of hydraulic, collision and overload (%)
Internal causes (design error, construction mistake, lack of maintenance, material defect); external causes (hydraulic, collision, overload, environmental degradation, earthquake, fire, wind, storm, etc.)	Hydraulic (52.9%), collision (11.7%), overload (8.7%), environmental degradation (8.5%), earthquake (3.4%)	85.3	73.3
Internal causes (design error, construction mistake, lack of maintenance, material defect); external causes (hydraulic, collision, overload, environmental degradation, earthquake, fire, wind, storm, etc.)	Hydraulic (47.2%), collision (15.3%), overload (12.7%), environmental degradation (6.7%), construction mistake (3.6%)	85.5	75.2
Natural causes (hydraulic, earthquake, environmental degradation, wind, fire, etc.); human causes (design error, construction mistake, demolition mistake, lack of maintenance, collision, overload, human activity, etc.)	Construction mistake (37.5%), hydraulic (22.5%), collision (16.5%), overload (9.8%), design error (2.3%)	88.6	48.8
Construction phase (design error, construction mistake, lack of supervision, etc.); service phase (design error, construction mistake, lack of maintenance, material defect, hydraulic, collision, overload, earthquake, etc.)	No statistics	–	–
Natural causes (hydraulic, earthquake, environmental degradation, wind, fire, etc.); human causes (design error, construction mistake, lack of maintenance, collision, overload, human activity, etc.)	Hydraulic (45.9%), construction mistake (27.3%), overload (10.8%), collision (8.3%), lack of maintenance (2.5%)	94.9	65.0
Construction phase (design error, construction mistake, lack of supervision, etc.); service phase (design error, construction mistake, lack of maintenance, material defect, hydraulic, collision, overload, earthquake, etc.)	Construction mistake (26.2%), hydraulic (17.9%), overload (14.5%), collision (14.0%), geological disaster (2.2%)	74.9	46.4
Design error, construction mistake, lack of supervision, fatigue, collision, overload, blast, fire, hydraulic, earthquake, etc.	Construction mistake (32.5%), overload (18.5%), hydraulic (13.9%), collision (6.6%), design error (4.6%)	76.2	39.0
Force majeure (avalanche, flood, earthquake, terrorist attack, etc.), overload, collision, design error, scour, construction mistake and lack of maintenance, etc.	Force majeure (73.8%), collision and overload (12.3%), design error (8.8%), construction mistake (3.5%)	94.8	–
Natural causes (hydraulic, earthquake, environmental degradation, wind, fire, etc.); human causes (design error, construction mistake, lack of maintenance, collision, overload, human activity, etc.)	Construction mistake (28.6%), collision (18.7%), hydraulic (17.5%), design error (9.0%), overload (8.4%)	82.1	44.6
Natural causes (hydraulic, earthquake, environmental degradation, wind, fire, etc.); human causes (design error, construction mistake, lack of maintenance, collision, overload, human activity, etc.)	Construction mistake (33.4%), collision (19.6%), hydraulic (17.7%), overload (8.0%), design error (5.2%)	84.0	45.3

Table 1. Causes of Bridge Failure.

Specific Causes

Bridge failures are usually the result of multiple factors; the most important single cause is often used for failure classification. Table 1 presents the specific causes. The specific causes mainly include design errors, construction mistakes, lack of maintenance, material defects, earthquake, hydraulic, wind, fire, overload, collision, etc. Table 1 also lists the top 5 leading causes and their proportion of each investigation. The top 5 leading causes are design errors, construction mistakes, hydraulic, collision, and overload. There were a few bridge failures caused by the earthquake due to a lack of statistical data in those investigations. Therefore, earthquake was not among the top 5 leading reasons. The proportion of bridge failures caused by the top 5 leading causes exceeded 70.0%, reaching a maximum of 94.9%. In addition, extreme loads such as hydraulic, collision, and overload contributed to more than 40% of bridge failures in most investigations, reaching a maximum of 75.2%.

The Observation shows that the proportion of construction mistake and hydraulic were the highest, followed by collision and overload. The proportion of design errors was the least. Observation also shows that the proportion of construction errors in the United States was much lower than in other regions. That was because fewer new bridges were built in the United States during recent decades while new bridges were growing rapidly in developing countries, such as China. In addition, the proportion of floods was much higher than that in other regions. The reason was that 2 major flood disasters in 1993 and 1996 contributed to the proportion with almost 171 bridge failures. The following 5 specific causes were analyzed, and they were design error, construction mistake, hydraulic, collision, and overload.

Failure Mechanisms of Bridge Due to the Top 5 Leading Causes

1. Design Error

Design error is related to bridge failures caused by defects in design theory and carelessness of designers, which have certain concealment and are difficult to find the errors before the completion of the bridge and verify the causes after it fails. The design theory defects are mainly due to ignorance and cognitive limitations of human beings, and lack of sufficient understanding of the mechanism of bridges. For example, the collapse of the Quebec Bridge was due to insufficient understanding of the stability of members. The collapse of the Tacoma Bridge was due to insufficient understanding of the mechanism of wind on the bridge. The collapse of the I-35W Bridge was due to insufficient understanding of fatigue of truss bridge joints, (Fig. 1).

Figure 1. Bridge failures due to design errors (Defects in design theory)

In addition, structural calculation errors or blind application of codes by designers due to lack of experience and knowledge will lead to bridge failure. For example, Chirajara Bridge in Colombia collapsed during construction due to insufficient design of the bearing capacity of the lower beam of the bridge tower. The collapsed bridge is shown in Fig. 2. Designers and researchers gain experience from the failures, continuously develop and perfect bridge design theory. Thus, the number of bridge failures caused by design theory defects is decreasing. Moreover, the number of bridge failures caused by the carelessness of designers is also decreasing with the continuous improvement of the laws and supervision regulations.

Figure 2. Bridge failures due to design errors (Design mistake)

When designing a structure, designers should think of all aspects that could influence the consequence. For the application of new structures, new materials, and new technologies, strict and sufficient scientific argumentation should be carried out to ensure the safety of bridges. In addition, the safety factor of bridges with new structures, new materials, and new technologies should be improved to envelope many uncertainties. Moreover, uncertainties in calculations will not lead to serious consequences unless design a robust structure.

2. Construction mistake

Many investigations show that a surprising number of bridges collapsed as they were being built. Human factors dominate most of the bridge failures, such as unreasonable construction technology, structure calculation errors, illegal construction, equipment operation mistakes, etc. For example, workers do not adopt or arbitrarily change the construction scheme, making the construction work carried out in the wrong way, which probably leads to bridge failures. In addition, engineers need to do many calculations of temporary structures, such as brackets, steel trestles, temporary piers, etc. Inadequate consideration of the boundary conditions, loads, and material defects in the calculation may lead to temporary structure failure and even cause bridge failures.

In addition, construction monitoring is necessary for long-span bridges to ensure the safety of bridges during construction. However, small span bridges usually do not need construction monitoring, and their safety is not paid enough attention to. Construction mistakes not only cause a huge number of bridge failures but also lead to serious consequences.

Structural instability is a prominent problem during the construction of steel bridges, which is inseparable from the excessive attention to structural strength and neglect of structural stability in bridge design.

Fig. 3 shows 3 typical failure cases of steel bridges during construction. Fig. 3 (a) shows the overall buckling failure of a steel plate girder of the SR-69 Bridge in the United States. Fig. 3(b) shows the buckling failure of the compression chords of Morava Bridge in Italy. Fig. 3(c) shows the buckling failure of a steel plate of compression flange of a steel box girder of Rhine Bridge in Germany.

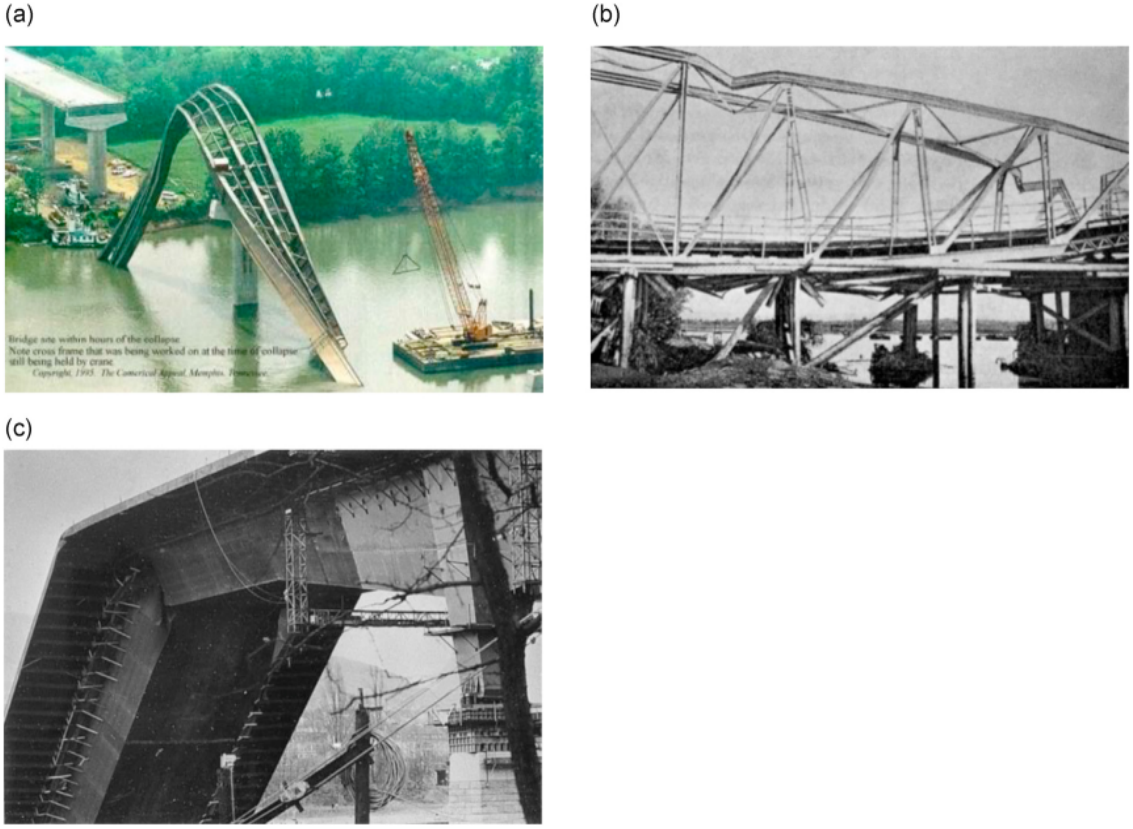

Figure 3. Steel bridge failures due to instability. (a) SR-69 Bridge. (b) Morava Bridge. (c) Rhine Bridge

From a technical perspective, it is necessary to improve the professional and technical level of technicians, so that they could have a clear understanding of the mechanical characteristics of structures, as well as the key points and difficulties of various types of bridge structures.

In addition, the design and calculation of the temporary structure must consider the reduction of material strength due to deteriorations, and the difference between calculated boundary conditions and actual boundary conditions. Attention should be paid to the inconsistency of structural section stiffness during construction and operation, to avoid bridge failure caused by instability during construction. Moreover, the structure safety factor should be improved for poor construction conditions and complex construction technology.

The failure rate is very high for steel bridges, which is inseparable from excessive emphasis on structure strength but lack of consideration on structure stability and fatigue in early years. Researchers need to strengthen their research on the stability and fatigue of steel bridges, as well as inspection and maintenance.

3. Hydraulic

Observation shows that a surprising number of bridges were destroyed by hydraulic, mainly including flood and scour. Heavy precipitation usually leads to flooding, which can collapse a bridge in a few different ways, such as scour, sand missing, softened bedrock, erosion, insufficient embedment depth, river convergence, debris impact or abrasion on bridge foundations, etc. Floods might destroy a bridge immediately or make it vulnerable to other causes of failure. Scour is defined as the erosion or removal of a streambed or bank material from bridge foundations due to flowing water, usually considered as long term bed degradation, contraction, and local scour. With an increase in scour depth, the lateral resistance of the soil supporting the foundation is significantly reduced, thus increasing the lateral deflection of the foundation head. Furthermore, when the critical scour depth is reached, bending buckling of the foundation may occur under the combined effect of a dead load of bridge superstructures and traffic load.

The failed cases are shown in Fig. 4. The causes of bridge failures caused by hydraulic are mainly classified into natural factors and human factors. For natural factors, rivers in some areas suffer from rare catastrophic floods, which exceed the ultimate limit state, thus causing the bridges to fail. The United States experienced 2 catastrophic floods in 1993 and 1996, with 171 bridge failures in these 2 years alone, making the proportion of bridge failures caused by floods far higher than other causes. Similarly, Guangdong Province of China experienced a devastating flood in 2013, with 316 roads cut off, 83 bridges collapsed and more than one hundred million dollars lost. For human factors, the most important factors are:

(i) lack of hydrological data upon which to base estimates of the magnitude of floods for design purposes;
(ii) lack of reliable methods for estimating scour at bridge piers;
(iii) inability to predict the occurrence of impact and accumulation of debris against the bridge structure.

In addition, inadequate bridge maintenance and management are also important human factors. For example, 24 bridges collapsed in the devastating floods in Sichuan Province of China in 2013. The survey results showed that disordered sand excavation caused by reconstruction after the Wenchuan Earthquake in 2008 led to an increase in riverbed gradient and erosion, resulting in a large number of bridge collapses in the short term. Similar to construction mistakes, the dominant structural type of failed bridges is small and medium beam bridges, followed by arch bridges, as well as a few cable-stayed bridges and suspension bridges. Hydraulic not only causes a high proportion of bridge failures but also leads to serious consequences.

To protect bridges from hydraulics, designers should select proper bridge sites, arrange bridge span properly, and ensure adequate foundation depth. Then, the bridge regulation and protection projects should be improved, and the direction of flood flow should be adjusted to reduce the impact and erosion of floods on bridges.

Finally, bridge maintenance work should be strengthened, and foundation scouring maintenance should be included in the preventive maintenance category, and the diseases should be found in time. The failure of the substructure usually leads to the failure of the superstructure. Therefore, the safety factor of the substructure should be no lower than that of the superstructure. In addition, structural safety should be ensured by strengthening structural capacity protection measures, improving structural toughness and redundancy.

Figure 4. Bridge failures due to hydraulic. (a) Foundation scouring. (b) Bridges submerged by flood. (c) Bridge collapse due to flood

4. Collision

This type of bridge failure mostly happens due to the collision of ships and vehicles. The ships or vehicles depart from the established route and impact the bridge pier, resulting in bridge pier damage or collapse, and even the superstructure collapsing. In addition, insufficient clearance under the bridge or oversize ships and vehicles will impact the superstructure, resulting in damage to or collapse of the superstructure. Such failures are more common in vehicle-impacting overpasses.

Fig. 5 shows 3 typical bridge failures due to collisions. Observation shows that vehicles have hit about 61% of overpasses in the United States. Near 50% of the overpasses in Beijing have been hit by vehicles, and more than 20% of failed overpasses were damaged by collisions. The main causes of bridge failures caused by collisions are human factors mainly including illegal driving, fatigue driving, drunk driving, and inexperience of drivers, which lead to ships or vehicles impacting bridge piers or superstructures. The main factors of the bridge itself are that some overpasses have been built for a long time ago, the clearance is inadequate, and it is difficult to upgrade or rebuild, which cannot meet the transportation needs of large vehicles. In addition, the carelessness of the drivers can easily lead to bridge failures.

Researchers and engineers should further study the mechanism of bridge failures due to collisions by vehicles and ships. Management of over-high vehicles should be strengthened. For overpasses with insufficient clearance, height limit signs should be installed on the road in front of the bridge to prevent the bridge from being directly impacted by oversize vehicles. If necessary, the risk of collision should be avoided by engineering measures, such as lifting the girders, reducing the road surface, or dismantling and rebuilding, etc. In addition, reasonable structure selection can also reduce the risk of bridge collision. For example, the channel bridge should avoid the selection of deck arch bridge and half through arch bridge.

5. Overload

With the increase in traffic volume, the truckloads exceeded the limitations, resulting in bridge failures, especially for older bridges. Such bridge failures are common in developed countries. Some researchers found that the average service age of failed bridges due to overload in the United States was about 64 years. Besides, due to the increasing competition in the transportation market, vehicle overload has become more and more common and has raised serious concerns in developing countries such as China. For example, overturning collapses of single column pier bridges often occurred in recent years in China, the average service age of the overturned bridges did not exceed 20 years, and some even less than 1 year. In addition, overloads may contribute to an acceleration of fatigue damage of steel bridges. Fig. 5 shows some examples of bridge failures due to overload. Beam bridges are the dominant structural type of failure due to overload. The live load effect accounts for a large proportion of the total effect, which causes beam bridges vulnerable to overloads.

It is found that, 135 bridge failures caused by overloads, in which steel bridge failures dominated approximately 64% while concrete bridge failures dominated approximately only 11%. That was because most of the steel bridges were built earlier than concrete bridges in the United States. Thus bearing and overload capacity of steel bridges got much lower than that of concrete bridges.

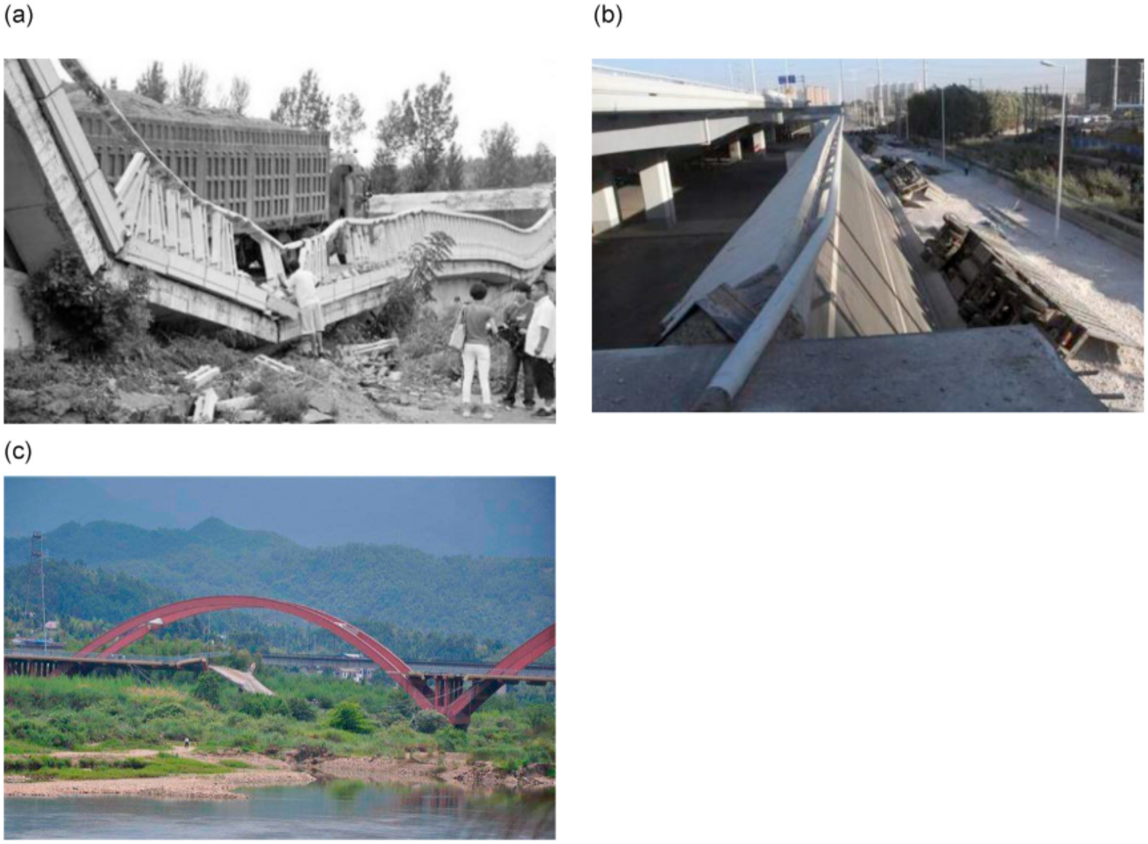

Figure 5. Bridge failures due to overload. (a) Girder collapsed. (b) Girder overturned. (c) Main girder of an arch bridge collapsed

We cannot improve the live load level to meet overload demand, which will cause great waste of resources. Overload should be treated as an extreme event. On one hand, the laws and regulations must be observed and strictly enforced, and those who break the laws must be prosecuted. On the other hand, it is critical for bridges to have sufficient redundancy and capacity protection measures to reduce the probability of bridge failure due to overload.

BRIDGE FAILURE CASE STUDIES

Design error, construction mistakes, hydraulic, collision, and overload are the top 5 leading causes of bridge failures. And the typical characteristics of the 5 leading causes had been discussed in this course. Thus, further analysis of bridge failure cases due to the 5 leading causes will be done in this chapter. These 5 failed bridges are FIU Pedestrian Bridge (**design error failure**), Marcy Bridge (**construction mistake failure**), Houfeng Bridge (**hydraulic failure**), Interstate 5 Skagit River Bridge (**collision failure**) and viaduct over Xigang Road (**overload failure**).

1. FIU pedestrian bridge (design error failure)

The FIU Pedestrian Bridge was a pedestrian bridge located in the Miami area of Florida, USA. The entire pedestrian bridge was 97.5 m long, with its central tower measuring 32.9 m above the ground. The completed bridge had the look of a cable-stayed bridge with a pylon and multiple cables attached to the canopy. However, the main span of the bridge was designed as a concrete truss bridge, which was self-supporting without the cables, i.e., the pylon and cables were just for aesthetic purposes. The construction of the entire bridge was scheduled to be finished by early 2019 and was built using the accelerated bridge construction (ABC) method. After being precast near the highway, the main span of the bridge was transported and placed on the bridge piers by 2 transporters (Fig. 6(a)). On March 10, 2018, the main span of the bridge collapsed, resulting in 6 fatalities and 10 injuries (Fig. 6(b)). The National Transportation Safety Board (NTSB) found that the concrete and steel materials used were within specifications, post-tensioning equipment was operating normally. NTSB determined the probable cause of the collapse was ***the calculation errors of load capacity*** made by FIGG Bridge Engineers. FIGG design resulted in less steel reinforcement and diminished resistance to critical interface shear demand, and member 11/12 nodal region contained pipe sleeves, resulting in void spaces. Re-tensioning of member 11 provided additional force across compromised interface shear plane, resulting in the collapse of the bridge. In addition, the truss bridge was non-redundant because it provided only a singular load path. However, designers determined the bridge was a redundant structure and then erroneously used a redundancy factor of 1.0, which is commonly used for structures with redundant load paths, reducing the safety of the structure.

The pre-stressed reinforced concrete truss is an uncommon structure. The design of this kind of structure should fully consider the characteristics of the structure itself, and avoid blindly applying the specification for common structures. When necessary, experimental research should be carried out, and the safety factor should be improved. In addition, the design of truss bridge should follow the principle of "strong joints and weak members", which means that joints do not fail before members.

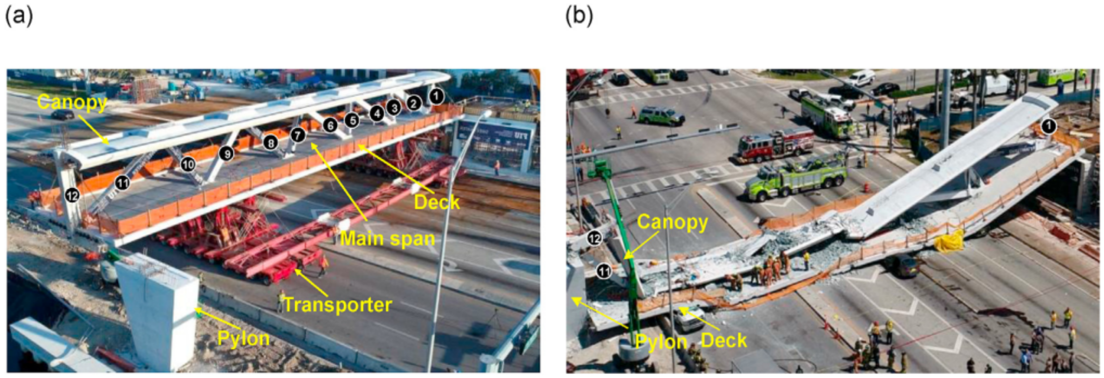

Figure 6. Collapse of FIU Pedestrian Bridge. (a) Before collapse. (b) After collapse.

2. Marcy Bridge (construction mistake failure)

Marcy Bridge was designed to span approximately 51.8 m across a new extension of the Utica-Rome Expressway in Marcy, New York, USA. The bridge was intended to carry pedestrian traffic and small emergency vehicles only. The design consisted of a single trapezoidal steel tub girder with a composite reinforced concrete deck (Fig. 7(a)). The tub girder had internal diaphragms and struts to prevent distortion of the cross section during shipping and erection; it did not have top lateral bracing (Fig. 7(b)). It was fabricated in 2 sections that were spliced on site while supported by cranes; the erection was done without false work or shoring. The steel tub girder had been erected, including all stay-in-place forms, and the concrete was being placed starting at the ease (fixed bearing) end on the day of the incident. The bridge collapsed during the casting of the deck, shortly after placement of the wet concrete had passed midspan, injuring 9 workers and killing 1 (Fig. 7(c)).

Based on eyewitness accounts and the position of the girder after the accident, it was evident that the failure mode was lateral-torsional buckling of the steel tub girder in which the entire girder cross-section participated; local buckling of the compression flange did not contribute. While bracing requirements appear in bridge design standards in general terms, top flange lateral bracing was not an explicit requirement of the 16th AASHTO Standard Specifications for Highway Bridge, adopted by New York State at the time of design of the Marcy Bridge.

The fundamental lesson to be taken from the tragic collapse of the Marcy Bridge is that designers and erectors must consider global lateral torsional buckling mode when evaluating the constructability of trapezoidal tub bridges without false work or shoring. Because of the tragedy, this lesson has already been incorporated into current design specifications, which now address this failure mode, typically by the use of tip flange diagonal bracing.

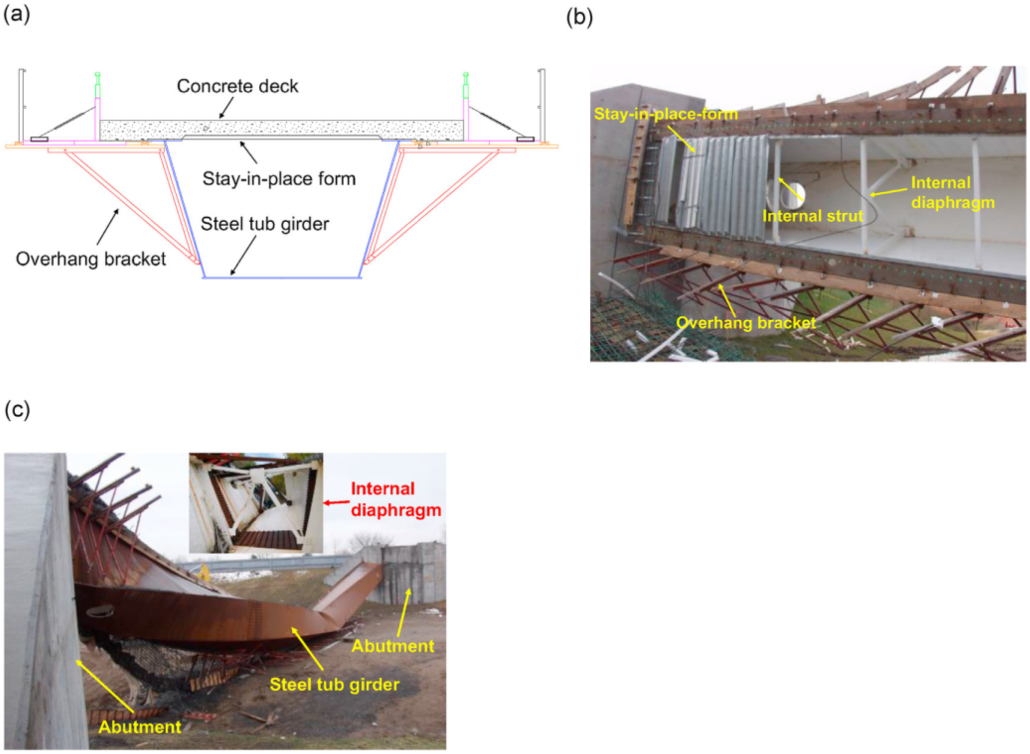

Figure 7. Collapse of Marcy Bridge. (a) Cross section. (b) Post collapse. (c) Collapsed steel tub girder

3. Houfeng Bridge (hydraulic failure)

The Houfeng Bridge, which was opened to traffic in 1990, was a four-lane, two-way, provincial highway 13 bridge that spanned the Da-Chia River in central Taiwan. The length of the bridge was 640 m with 16 spans. The superstructure consisted of steel plate girders with a reinforced concrete slab deck. Each pier consisted of four 2-m-diameter reinforced concrete cylinders tied with a reinforced concrete capping beam. All the caissons were originally designed to be completely embedded within the riverbed. During Typhoon Sinlaku in September, 2008, which pelted Taiwan with strong winds and heavy rain, 6 bridges collapsed and 8 cars were buried by a landslide with a total casualty of 7 deaths and 17 injuries. Among these 6 collapsed bridges, the Houfeng Bridge, which collapsed at 6:50 PM on September 14, 2008, was one of the 10 extremely scour-critical bridges previously identified by the Directorate General of Highways (DGH). Fig. 8 shows the flow condition upstream of the Houfeng Bridge after the recession of the flood on September 24, 2008. One may clearly reduce from the photograph in the figure that the direct cause of failure is the damage to Pier 2 (P2). The investigation results showed that the failure of Houfeng Bridge was related to long term and short term general scour of the riverbed, contraction, bend, pier, and jet scour. Some of these were man-induced and the others were attributed to natural causes in the form of typhoon-induced floods and earthquake-induced bed degradation. Chi-Chi Earthquake, for example, which took place on September 21, 1999, had a direct influence on long term river bed degradation and led to an average lowering rate of the river bed at the Houfeng Bridge of approximately 0.5 m/year or a total of 4.51 m over the past 9 years from 2008. The long term general scour rate in a river, whether it is attributed to seismic or flood origin, must be evaluated through annual cross-section surveys or the conduct of numerical models. Moreover, proper precautions must be taken if damage to or failure of hydraulic structures and riverbed monitoring technologies need to be improved, especially under high flood flows.

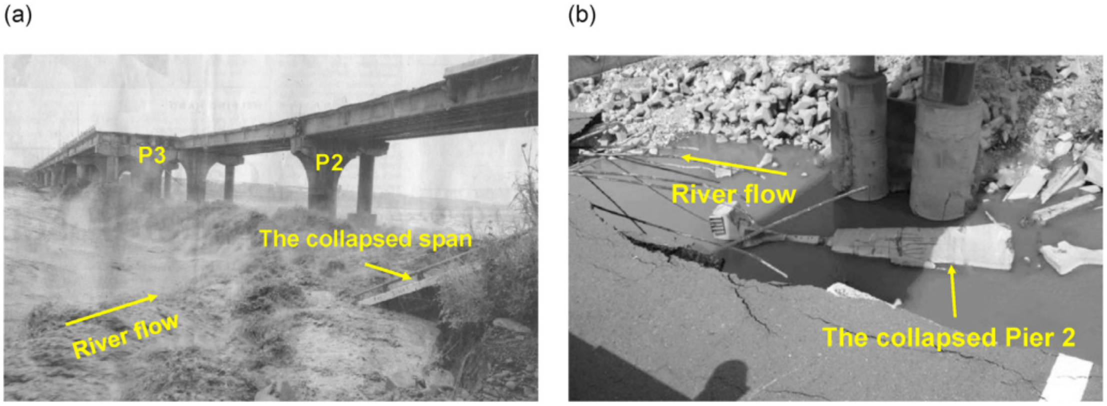

Figure 8. Photographs of Houfeng Bridge. (a) Bridge collapsed. (b) Remnant of pier 2

4. Interstate 5 Skagit River Bridge (collision failure)

Interstate 5 Skagit River Bridge consisted of 12 spans with a total length of 1,111 feet 9 inches. The 4 center spans (spans 5,6, 7, and 8) crossing the Skagit River were independent through truss span. Each truss span was 160 feet long and made of riveted steel sections. The bridge was completed and opened to traffic in 1955. On Thursday, May 23, 2013, at about 7:05 PM, a truck-tractor was traveling south on Interstate 5 near Mount Vernon, Washington. The oversize combination vehicle had a permit for the route of travel and was led by a pilot vehicle. As the oversize combination vehicle traveled across the bridge, its oversize load struck the bridge, damaging the structure. The span 8 of the 12-span bridge collapsed into the Skagit River, causing 2 passenger vehicles to fall into the river and injuring 3 people.

Fig. 9 shows the collapsed Interstate 5 Skagit River Bridge. The NTSB determines that the probable cause of the bridge collapse was the oversize load struck sway brace 4 in span 8 on the west truss, causing deformation of the adjacent vertical member (L4-U4), which pulled the attached upper chord member (U3-U5) downward, causing a buckling failure in that upper chord member at node U4. Besides, the truss bridge was a non-load-path-redundant structure, buckling of the upper chord resulted in the failure of the east truss and collapse of span 8. The bridge was in good condition and fully met the operational requirements before it collapsed, although it had been in operation for 58 years. The reason why the bridge collapsed was due to deficiencies in the interdependent system of safeguards for oversize load movements. These deficiencies included:

(i) Insufficient route planning by the transportation company and the driver;
(ii) Failure of the certified pilot vehicle driver to perform required duties and to communicate potential hazards;
(iii) Inadequate evaluation of oversize load permit requests and no provision of low clearance warning signs in advance of the bridge by the Washington State Department of Transportation.

For over-high vehicles, the height limit of the bridge should be known in advance before travel, and the driving route should be reasonably planned. It is necessary to arrange pilot vehicles before over-high vehicles, and real-time detect the bridge clearance to be passed, so as to ensure the safe passage of vehicles. In addition, for through truss bridge, attention should be paid to the clearance difference of different lanes, and height limit signs should be set for each lane if necessary.

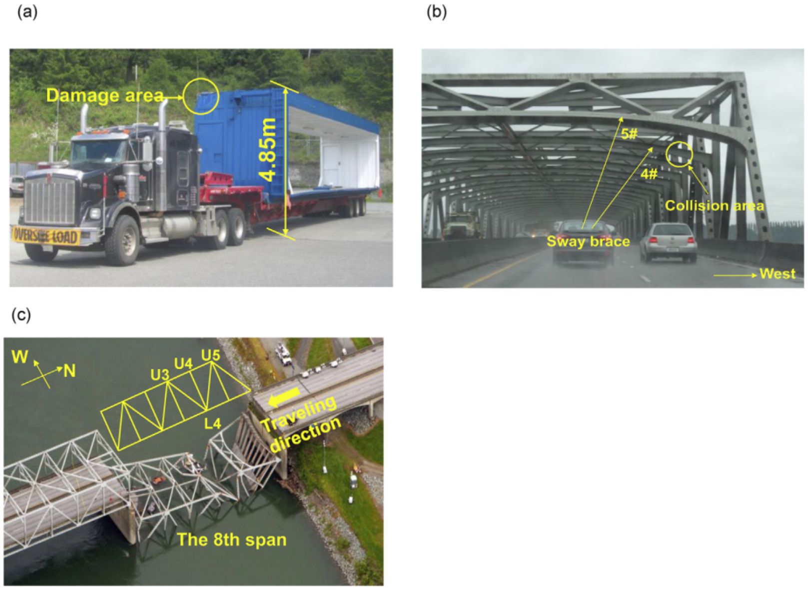

Figure 9. Collapsed Interstate 5 Skagit River Bridge due to collision. (a) The oversize combination vehicle. (b) Sway brace of the truss. (c) Collapsed span.

5. Viaduct over Xigang Road (overload failure)

The collapsed bridge was a viaduct over Xigang Road in Xishan District of Wuxi, Jiangsu Province, China. The bridge had a total length of 82 m, was built in December, 2004, and opened in December, 2005. It consists of 3 spans (22 + 35 + 25) m (Fig. 10(a)). The superstructure is a concrete box girder supported by 2 piers, and both of the 2 interior piers are of single-column design with only one pot bearing for each while 2 end piers are double-column design with one pot bearing for each. About 18:06 PM on October 10, 2019, 2 fully loaded trucks were moving in tandem on the left lane (twolane bridge) when the whole superstructure of the bridge overturned and then suddenly collapsed (Fig. 10(b)). 3 people were killed and 2 injured, resulting in a direct economic loss of 8.23 million dollars. Based on the scene of the collapse, the failed bridge girder still showed good integrity without apparent smash and cracks. After detailed investigation and argumentation, the experts ruled out bridge design errors, construction mistakes, and deficiency of maintenance, agreeing that overloading was the primary cause. These 2 trucks were found to be significantly overloaded with 54.32 and 170.96 t, respectively. The total weight of all of the trucks was 225.28 t, which was equal to 27.47 kN/m along the bridge and 1.85 times heavier than the load capacity of the bridge required by the bridge design specifications. There were nearly 10 similar bridge collapses in China from 2007 to 2019, and the common characteristics of the collapsed bridges are that: (i) the spans are continuous girders, and the superstructure is an integral box girder supported by compression bearings; (ii) double bearings at the end piers and single-column piers in between. ***Special attentions need to be given to this type of bridge to evaluate its safety. On the one hand, the government should establish and perfect laws and regulations to standardize the transportation market, governing overload originally. On the other hand, researchers should develop scientific and reasonable anti-overturning calculation methods and protective measures, and write in the design specifications***

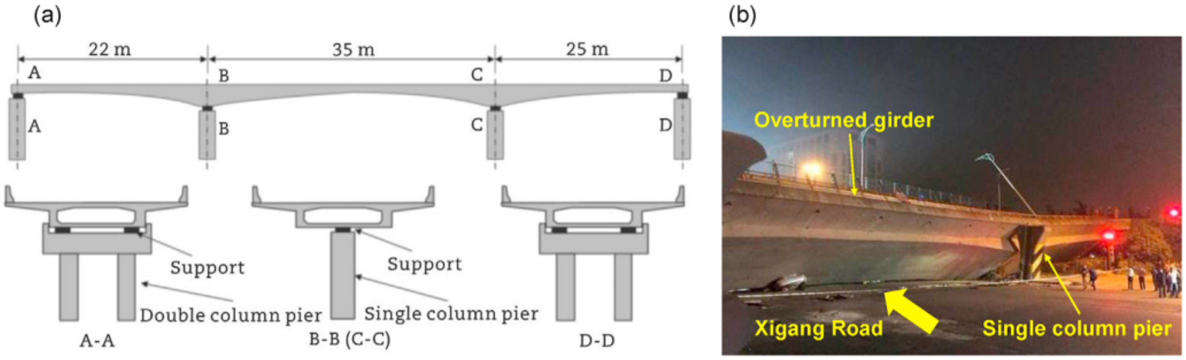

Figure 10. Collapse of Viaduct over Xigang Road. (a) Bridge diagrammatic drawing. (b) Overturned girder.

CONCLUSIONS

Bridge failure is always an unfortunate incident because of the loss of human life and economic losses. However, much knowledge and experience have been gained from the lessons of real bridge failures. Based on statistical analysis and findings, the following conclusions can be drawn:

1) Design error, construction mistakes, hydraulic, collision, and overload are the top 5 leading causes of bridge failures, resulting in more than 70% of the bridge failures. Causes of bridge failures are closely related to structural type, type of use, material type, and service age.

2) The failure rate of steel bridges is very high, which is inseparable from excessive emphasis on structure strength but lack of consideration on structure stability, fatigue and maintenance in early years. More researches need to be performed on the stability and fatigue of steel bridges, as well as inspection and maintenance.

3) Extreme loads such as flood, collision, and overload contribute to a large number of bridge failures because of the lack of extreme loads data and design theory defects. It is critical for such bridges to have sufficient redundancy and capacity protection measures to reduce the probability of bridge failure due to extreme loads.

4) Previous statistical methods and classification methods for the characteristics and causes of bridge failures lack unified standards, and a more scientific method needs to be established. A comprehensive electronic database on bridge damage and failures needs to be developed to establish damage models and conduct forensic studies to improve the design theory and specifications.

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