IABSE-JSCE Joint Conference on Advances in Bridge Engineering-III, August 21-22, 2015, Dhaka, Bangladesh. ISBN: 978-984-33-9313-5
Amin, Okui, Bhuiyan, Ueda (eds.) www.iabse-bd.org

Bridge collapses around the world: Causes and mechanisms

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ABSTRACT: Failures of bridges have occurred ever since bridge building started thousands of years ago. A large part of the technical knowledge associated with bridge engineering today is based on the past failures of bridges. In the past century, bridge engineers learned substantially from studying historical failures of bridges. Each bridge failure has its unique features which makes it difficult to generalize the causes of failures. This paper reviews the more common causes and mechanisms of some bridge failures around the world. These factors are classified as natural factors (flood, scour, earthquake, landslide, wind, etc.) and human factors (improper design and construction method, collision, overloading, fire, corrosion, lack of inspection and maintenance, etc.). The collapse modes of some historic bridges are reviewed. Moreover, some of the bridge failures which have taken place in Bangladesh over the last few decades are also discussed.

1 INTRODUCTION

The Association of American State Highway and Transportation Officials (AASHTO) defines a bridge as *''a structure, including supports, erected over a depression or an obstruction such as water, highway, or railway, having a track or passageway for carrying traffic or other moving loads and having an opening measured along the center of the roadway of more than 6 m between under-copings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it may also include multiple pipes where the clear distance between openings is less than half of the smaller contiguous opening.''*(AASHTO, 1999).

The report of the National Bridge Inventory (FHWA 2001) estimated that 691,060 bridges existed in the United States alone at that time and the Federal Highway Administration rated nearly 30% of these bridges as deficient. Wardhana and Hadipriono (2003) concluded that in United States, the most frequent reasons of bridge failures were not due to design and construction fault but due to floods and collisions. Bridge overload and lateral impact forces from trucks, barges/ships, and trains resulted in around 20% of the total bridge failures.

The principal causes of bridge failures were categorized as deficiencies in design, detailing, construction, maintenance, use of weak materials, and inadequate consideration of external events. Deficiency in design constitutes errors, mistakes, oversight, omission, or conceptual flaw that could have taken place during the design process of the bridge. Detailing is a process between design and construction periods, in which the details of the structural design are prepared for their implementation through shop drawings. Design detailing is commonly performed by the contractors and approved by the engineers. Changes are often made emphasizing workability and constructability of the facility.

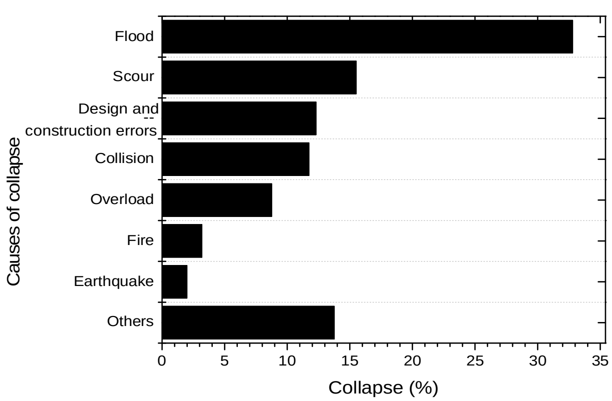


Figure 1. Distribution of causes of the 503 reported bridge collapses during the period between 1989 and 2000 in the United States (data from Wardhana and Hadipriono 2003)

2 CAUSES AND MECHANISMS OF BRIDGE FAILURES

2.1 *Natural Phenomenon*

Several natural hazards like flood, scour, wind, earthquake, landslide, debris flow, and storm surge are unavoidable and are among the root causes of failures of many bridges. A brief summary of causes and mechanisms of bridge failures due to different natural hazards are summarized in the following sections.

2.1.1 *Earthquake*

Earthquakes lead to vertical and horizontal ground motions that can result in the failure of bridges. The most common damage includes shear-flexural failure of the bridge pier columns, expansion joint failure, shear key failure, and girder sliding in the transverse or longitudinal directions due to weak connections between girders and bearing (Qiang et al. 2009). In addition, both the vertical and horizontal ground motions may cause the liquefaction of the soil at the bridge foundations, which can greatly reduce the load-carrying capacity of the foundations leading to bridge collapse.

2.1.2 *Wind*

Forces and vibrations induced by wind have led to a large number of failures. The Tacoma Narrows Bridge disaster is one of the best examples of bridge collapses which was triggered by wind. Wind induced aerostatic and aerodynamic forces are major design challenges in designing bridges, especially for flexible long-span bridges. Boonyapinyo et al. (1994) categorized the aerostatic instability into two types according to the modes of static instability, viz. torsional divergence and lateral-torsional buckling. Aerodynamic vibration is usually caused by three different types of oscillations viz. flutter, buffeting, and vortex-induced oscillation (Scanlan 1998). These forces lead to large displacements and stresses that may exceed the capacity of bridge structures and resulting in the collapse of bridges (Scanlan 1998).

2.1.3 *Cyclone*

In addition to the high pressure due to extreme winds in case of cyclones, the hydrodynamic forces caused by storm surge resulting from the tropical cyclones cause severe damages in the bridges in coastal areas. The high transverse wind speed combined with the surge in the water level resulting from a reduction in the atmospheric pressure raise the water level to an elevation that is able to strike the superstructure of bridges along the coast. Based on the several observed failure modes of bridges due to cyclone, it is obvious that the connections between the bridge deck and piers play the most important role to withstand the cyclone induced wave loads (Deng et al. 2015).

2.1.4 *Scour*

Scour is a phenomenon in which the level of the riverbed becomes lower under the effect of water erosion, leading to the exposure of bridge foundations. This happens either because of the increase of flow speed around the river piers or because of the long time erosion of the riverbed. The scour phenomena depend on the flow rate, speed, type and condition of the riverbed, width and depth of the river (Biezma et al. 2007). 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 or local buckling of the foundation may occur under the combined effect of the dead load of bridge superstructures, the traffic load and/or lateral loads.

2.1.5 *Landslide*

Landslide occurs mainly due to water saturation, earthquake, or volcanic eruption, and it may result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these materials (Iverson 2000). These moving slope-forming materials, when hitting the bridge, may lead to severe damage or even collapse of the bridge.

2.2 *Manmade factors*

In addition to the natural factors, human factors, including imperfect design and construction method, collision, vehicle overloading, fire, attacks by enemy forces or terrorists, lack of inspection and maintenance, etc., may also result in bridge collapses. These factors are discussed in the following sections.

2.2.1 *Design and construction errors*

Many bridges have collapsed due to the imperfect design; use of materials with poor quality Use of an inappropriate construction method have led to bridge collapses in the construction phase (Abdelhamid and Everett 2000). The choice of material based on location and environmental factor plays an important role; for example, construction materials, especially iron and steel are not resistant to weather or other corrosive influences, unless special measures are adopted. The collapse of the West Gate Bridge in Australia in 1970 was due to the poor design and the inappropriate construction methods used (Biezma and Schanack 2007), while the failure of the Kutai-Kartanegara Bridge in Indonesia in 2011 was due to overstress in the connections that resulted from an imperfect connection design and questionable material selection (Kawai et al. 2014). Therefore, strict process control and proper supervision can effectively reduce the probability of this type of bridge failure. A surprising number of bridges collapse as they are being built. Unfortunately, some of the deadliest bridge collapses in history have occurred during the construction of bridges. While a functional bridge may only have a few vehicles on it when it collapses, it takes hundreds of workers to build a bridge - all of whom may be in dangerous positions in case of collapse. The 1907 collapse of the Quebec Bridge crossing the St. Lawrence River at Quebec City shows how engineering miscalculations can lead to disaster. The bridge was only partially constructed, but parts were already bending and breaking from the weight of the bridge itself. Engineers were concerned, but unable to take action swiftly enough. When it collapsed, 74 workers were killed (Akesson 2008). Amazingly, when the bridge was being rebuilt in 1916, it collapsed again, killing 13 more workers. It was finally completed in 1917 and remains in use today.

2.2.2 *Overloading*

Incorrect assumption of loads is another major cause of collapse. Truck overloading usually causes fatigue problems in bridge components and can shorten the service life of bridges (Wardhana and Hadipriono 2003; Biezma and Schanack 2007). In some extreme cases, the weight of the overloaded trucks may exceed the load-carrying capacity of the bridge and directly cause bridge collapse.

2.2.3 *Collision*

Collision due to vessel impact causes serious damages to bridges. Several collapses in bridges initiated by the local component failure resulting from collision have been reported (Yuan 2005). Lu and Zhang (2013) studied the failure process of the Jiujiang Bridge over Xijiang River in Guangdong province in the People's Republic of China, which collapsed on June 15, 2007, due to vessel impact and pointed out that the progressive failure of three consecutive spans resulted from the separation of structural elements and the centrifugal force of the falling bridge deck. To account for vehicle collision, the AASHTO (2012) code requires that the abutments and piers located within a distance of 9.144m to the edge of roadway shall be designed for an equivalent static force of 2,669 kN, which is assumed to act in a direction of 0 to 15° to the edge of the pavement in a horizontal plane, at a distance of 1.542m above the ground.

2.2.4 *Lack of inspection and maintenance*

Usually bridges are designed and constructed to serve for a long time, at least 100 years. However, bridges in service are constantly subject to not only dead and live loads, but also attack by the environment. As a result, bridges experience progressive deterioration, which, when exceeding a certain threshold level, can cause serious problems. The deterioration mechanism is influenced by various factors including material properties, environmental conditions, live load situation (Kim et al. 2013). The risk of bridge deterioration cannot be completely eliminated - however, a good maintenance program including regular inspection and proper rehabilitation will slow down this process (Biezma and Schanack 2007).

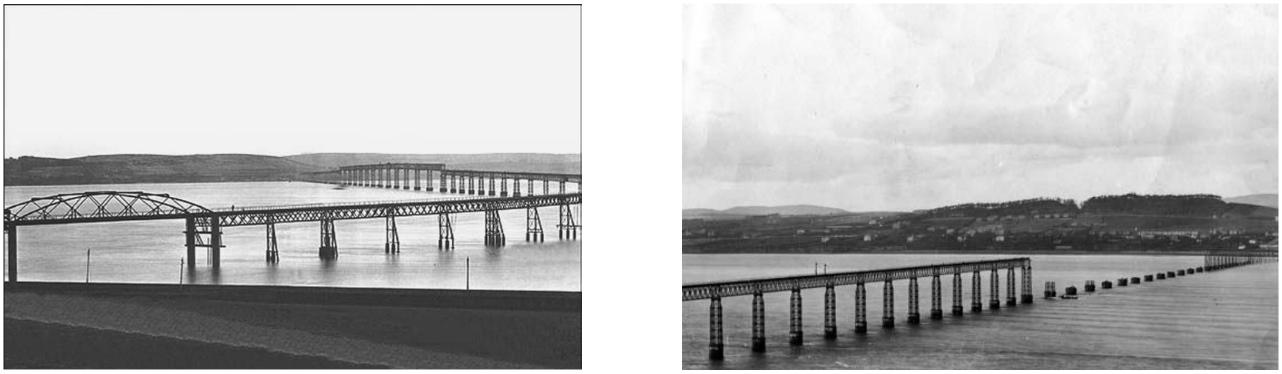
2.2.5 *Fire*

Fires on bridges are commonly caused by the collision of vehicles such as fuel tankers or freight trucks and multiple vehicle collisions or construction accidents (Bai et al. 2006). Increase of temperatures (in the range of 800–900°C) within the first few minutes of fire initiation and then the temperature can rise to 1,000°C or higher in the first 30 min (Stoddard 2004). The rapid rise in temperature can create large thermal gradients in the structural members and consequently cause spalling of the concrete and local buckling of steel members (Peng et al. 2008). Moreover, fires can lead to a significant decrease in the load-carrying capacity of the structural members due to reduction in the strength and stiffness of materials, which can further lead to partial or full collapse of bridges (Bai et al. 2006). For example, the Galata Bridge, a floating bridge spanning the Golden Horn in Istanbul, Turkey, was badly damaged in a fire in 1992 and had to be abandoned.

3 NOTABLE BRIDGE FAILURES

3.1 *Tay Bridge (1879)*

The collapse of the Tay Railway Bridge near Dundee, Scotland, on 28 December 1879, was the worst structural failure to have occurred in Britain at the time, and in terms of both lives lost and the size of the failed structure it still retains this dubious distinction. The 3.5 km long bridge was the longest railway bridge in the world at that time and it was regarded as an outstanding achievement (Figure 2a). Figure 2b demonstrates the extent of the devastation, with ten piers swept totally clear of the towers which once stood upon them. Although wind loads contributed to the disaster, the bridge was already severely defective owing to failure of its most important stabilising elements (Lewis and Reynolds 2002).

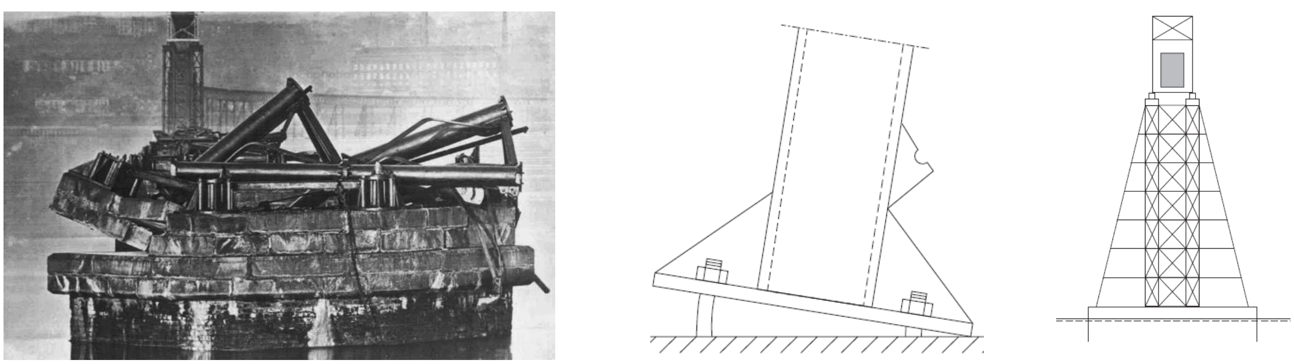


(a) (b)

Figure 2. Images of Tay bridge, (a) Tay bridge just after completion in 1878, (b) Collapsed high girder section of the bridge with twelve pier platforms almost completely swept off from their high girders (Lewis and Reynolds 2002).

The maximum pressure came from the wind gusts, producing not only very large deflection of the truss columns in the wind direction, but also initiating resonant vibration (swaying) which amplified the forces at the base of the truss columns and the deflections of an already weakened structure, which finally became too much for the bridge to carry (Figure 3a-b). The Court of Inquiry (1879) concluded that "the fall of the bridge was occasioned by the insufficiency of the cross bracing and its fastenings to sustain the force of the gale''. The high-girder section of the bridge would definitively have benefited from an extra pair of straddling legs (like the intuitive position of a human body expecting a horizontal thrust), stabilizing the truss columns and drastically lowering the strain due to severe winds (Figure 3c).

In addition, there was also an incident during the construction of the bridge that very well could have contributed to the swaying of the bridge even during calm weather (Akesson 2008). A high girder section was damaged (slightly bent) during the lifting procedure (it was dropped into the sea), and yet this section was used. The drivers reported of a curvature in the track that produced a horizontal, transverse thrust each time the engine passed that particular section.

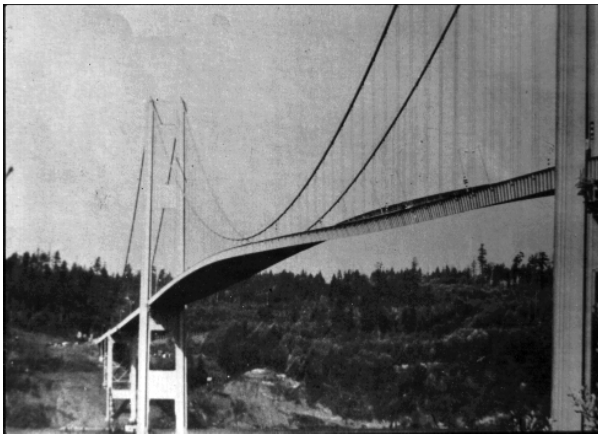


(a) (b) (c)

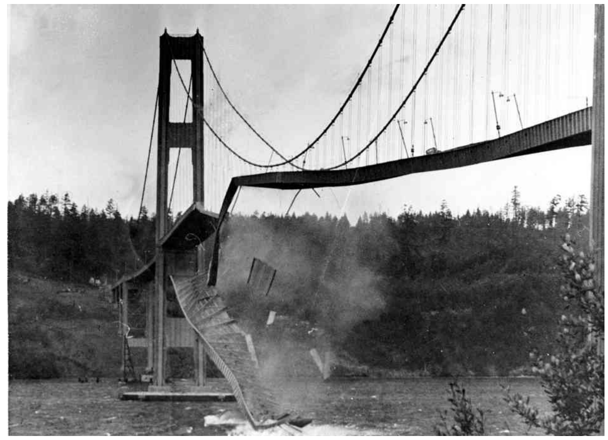
Figure 3. Mechanism of collapse (a) One of the broken piers of the collapsed high-girder bridge section (looking north). (http://taybridgedisaster.co.uk/) (b) Elongated and deformed anchorage bolt on the tension side of the cylinder base plate (Akesson 2008), (c) An extra pair of straddling legs would most probably have saved the Tay Bridge (Akesson 2008).

3.2 *Tacoma Narrows Bridge (1940)*

The collapse of the Tacoma Narrows Bridge near Seattle, USA, is perhaps the best recorded and documented bridge failure in bridge engineering history – the spectacular and prolonged failure process was captured on extensive live footage, giving a unique document for the investigation committee as well as for the engineering society at large. The footage has since then been used in civil engineering classes all around the world for educational purposes, and it is a very instructive video showing the consequences of neglecting dynamic forces in the design and construction of suspension bridges. On 7 November 1940, with a wind velocity of about 60 kph, the bridge began twisting and oscillating violently (Figure 4a). The bridge was twisting about 45 degrees in two waves, and oscillating up and down one meter in nine waves. The oscillations reached 8 meters as the bridge tore itself apart (Figure 4b) (Levy and Salvadori 1992, Feld and Carper 1997). The Federal Works Agency (FWA) investigated the collapse of the Tacoma Narrows Bridge and found that the bridge was well designed and well built. While it could safely resist all static forces, the wind caused extreme undulations which caused the bridge's failure.



(a)

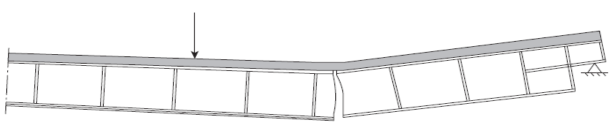


(b)

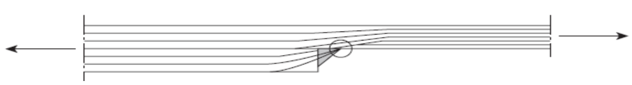
Figure 4. Tacoma Narrow Bridge, (a) The deflected side span on the east side, at the time of the collapse of the main span., (b)The first part of the collapse, where 183 meters of the main span tore away from the vertical hangers (suspenders) and fell into the waters below (University of Washington Libraries, Special Collections, UW 21422).

3.3 *Kings Bridge (1962)*

Kings Bridge in Melbourne, Australia, crosses over the Yarra River as well as over a railway and a couple of streets, in a north-southerly direction. Due to poor soil conditions it was decided to use high-strength steel in order to keep the self-weight of the I-girder bridge down. Fifteen months after opening of the bridge, on 10 July 1962, at 11 o'clock on a cold winter morning, as a 45-ton heavy vehicle was passing over the second span on the western carriageway – having approached the bridge from the south – this span broke and collapsed. It was concluded that the primary brittle fractures in these girders were due to the brittle nature of the steel. They were 'triggered' by the cracks present at the toes of the transverse weld at the cover plate ends (Figure 5a-d) (Akesson 2008).



(a)



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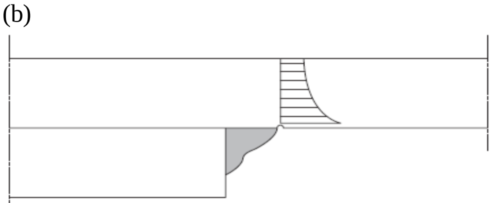
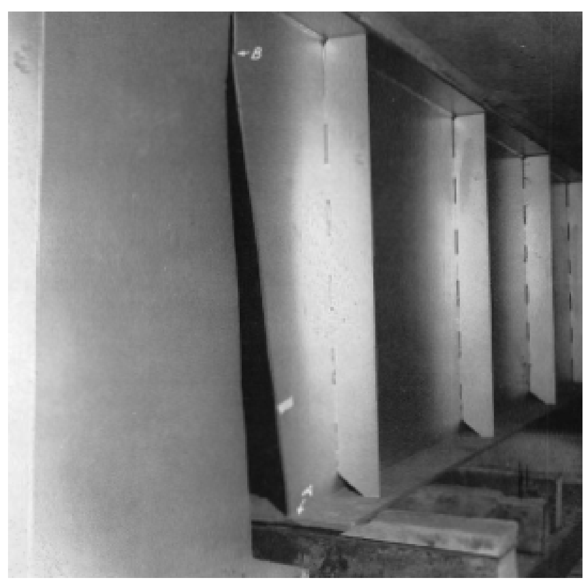




(d)

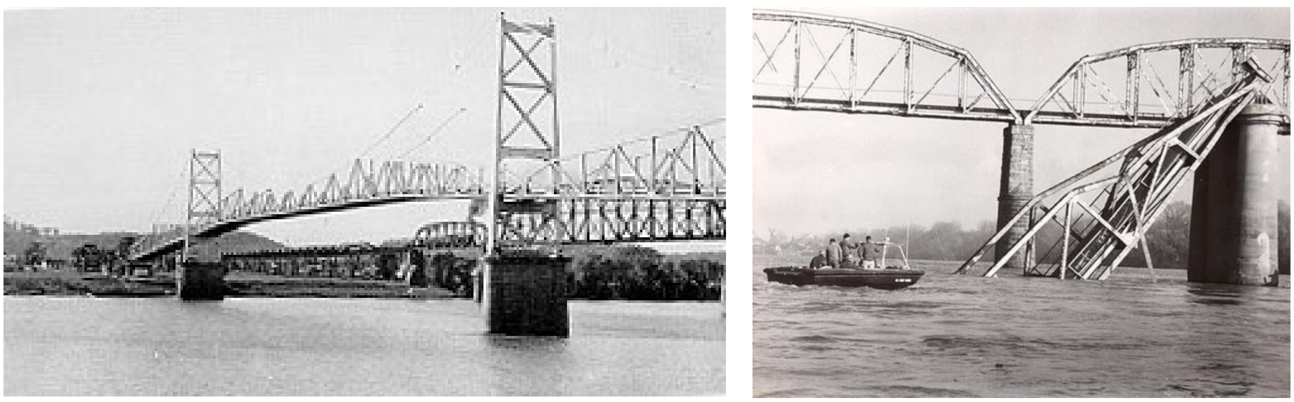
(c)

Figure 5. Kings Bridge (a) Fracture in girder in southern end , (b) The stress concentration effect at the weld toe, (c) Additional stress-raising effects from the roughness of the surface, and, especially, melting ditches, (d) Complete fracture of I-girder No. 1 on the western carriageway. The photo was taken inside the bridge looking north, in between girders No. 1 and 2 (Image taken from Akesson 2008)

The faulty design of the Kings Bridge was "as if all the lessons learnt from the failures of the welded bridges in Germany and Belgium in the late 1930's were completely forgotten - (cf. Hasselt Bridge collapse 1938)". In fact, the bridge at Rüdersdorf also failed due to transverse welding in a tension flange, so the mistake was here repeated.

3.4 *Silver Bridge (1967)*

On May 13, 1926, the 69th Congress of the United States enacted legislation (later amended December 23, 1926 and May 2, 1927) granting consent to the Gallia County Ohio River Bridge Company to construct a bridge across the Ohio River. The bridge was constructed in 1927-28 as a private venture by the West Virginia-Ohio River Bridge Corporation (Figure 7a). The eastern end of the bridge was situated at Sixth and Main Streets in Point Pleasant, W.Va., and the western end of the bridge connected with Ohio State Route 7, approximately 7 km north of Gallipolis, Ohio. After some 40 years of service, the bridge collapsed without warning on December 15, 1967 during the evening rush hour, when the bridge was crowded with heavy traffic. The collapse resulted in the loss of 46 lives and nine injuries (Figure 7b). A thorough investigation revealed that the collapse of the bridge was caused by the failure of the north eyebar of the north chain at the first panel point west of the Ohio tower. The eyebar had developed a cleavage failure at the lower position of its head. The tragedy of this bridge failure led to the approval of the 1968 National Bridge Inspection Standards by the U.S. Congress.

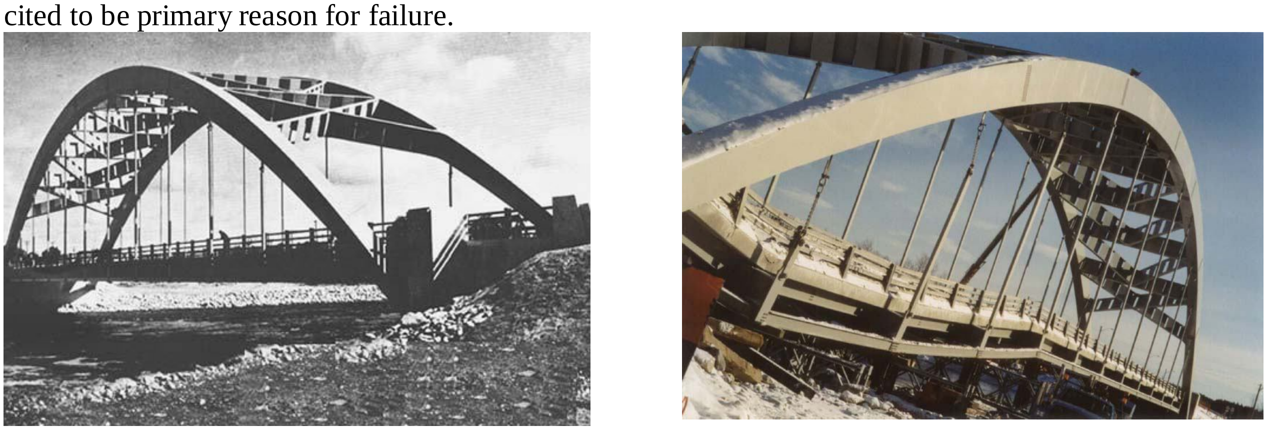


(a) (b)

Figure 6. Image of Silver Bridge, (a) View of Silver bridge before failure took place (http://wikipedia.org/wiki/Silver Bridge), (b) Image taken during rescue operation after failure of bridge (http://failures.wikispaces.com/Silver+Bridge+(Point+Pleasant)+ Collapse).

3.5 *Sgt. Aubrey Cosens VC Memorial Bridge (2003)*

In the small Canadian town of Latchford, in the province of Ontario, a 106.7m long suspended-deck steel arch bridge spanning the Montreal River was built in October 1960. On 14 January 2003, partial failure occurred under load of transport truck during severely cold temperatures. Fatigue fractures of three steel hanger rods cited to be primary reason for failure.



(a) (b)

Figure 7. Image of bridge (a) The Sgt. Aubrey Cosens VC Memorial Bridge, (b) Image of Bridge after failure took place. The three fractured hangers were still standing up after the collapse (Image taken from <http://www.thekingshighway.ca/latchford.html>).

4 COLLAPSE OF BRIDGES IN BANGLADESH

Thousands of bridges, which form important part of the rail and road infrastructure, have been constructed in Bangladesh over the last few decades. Every year, several bridges face distress due to natural or man-made factors mentioned in the earlier sections. Some examples are cited below.

In 1960, a RC deck girder bridge near Amin Bazar, Dhaka, failed due to poor detailing of deep girders making it difficult to compact the concrete, as a result of which the girder developed wide cracks at the bottom. Flood water washed away the caissons of Noyarhat Bridge near Dhaka during construction in the 1960s. After the attack of the severe Category V Cyclone Sidr on November 15, 2007, while people were waiting on a bridge in Kalapara, a village in the Patuakhali district, for relief materials to arrive, the bridge suddenly collapsed and killed four people and hundreds were injured (Figure 8a). Failure occurred on May 28, 2015 due to heavy loading in a Bailey Bridge over the Ichamoti River at Ambari, cutting off the road link in Dinajpur (Figure 8b) (UNB 2015). A local daily newspaper reported the most recent collapse where two tankers of an oil train submerged in water due to the failure of a rail bridge at Benguira in Boalkhali upazila, Chittagong (The Financial Express, 19th June 2015). The following section presents a summary of causes and mechanisms of failure of some bridges in Bangladesh.


(a)


(b)

Figure 8. Image of bridge after the collapse (a) image of the collapsed bridge at Kalapara, (b) Image of collapsed bridge at Ambari (Photo taken from Daily Star May 28, 2015) .

4.1 *Hardinge Bridge (1933 and 1971)*

The 1.62 km long steel truss railway bridge over the Padma River between Paksey and Bheramara, Pabna, known as the Hardinge Bridge, was designed and built during 1908-1915. It was the longest bridge in Bangladesh for over 80 years until the 4.8 km long Bangabandhu Bridge over Jamuna was completed in 1998. During its 100 years of service two major failure events occurred, one is natural (not of the bridge structure, but of the river training works) and the other (of the bridge superstructure and substructure) is manmade. On 25th of September, 1933, the turbulent flow resulting from a flood destroyed the right guide bank, initially 122 m, which later extended to 488 m (Warrier 1977, Ghoshal 2015). After the incident, immediate actions were taken by dumping of stones to restore the river training work (Ghoshal 2015). The second major damage occurred during the War of Liberation of Bangladesh in 1971. One of the 18.3 m steel spans – the 9th span from Bheramara side - fell off due to direct missile hit and the 12th span was blown off by explosives placed on the bridge span by the army as a part of war strategy. Detailed investigations were carried out afterward and it was decided to conduct the repair work of the bridge, which forms a vital transport link. To ensure the aesthetic view, identical members with higher grade of steel were selected. After completion of restoration work, the deflection of the bridge measured by running special trains on both tracks (Ghoshal 2015).

4.2 *Karnaphuli Bridge (1991)*

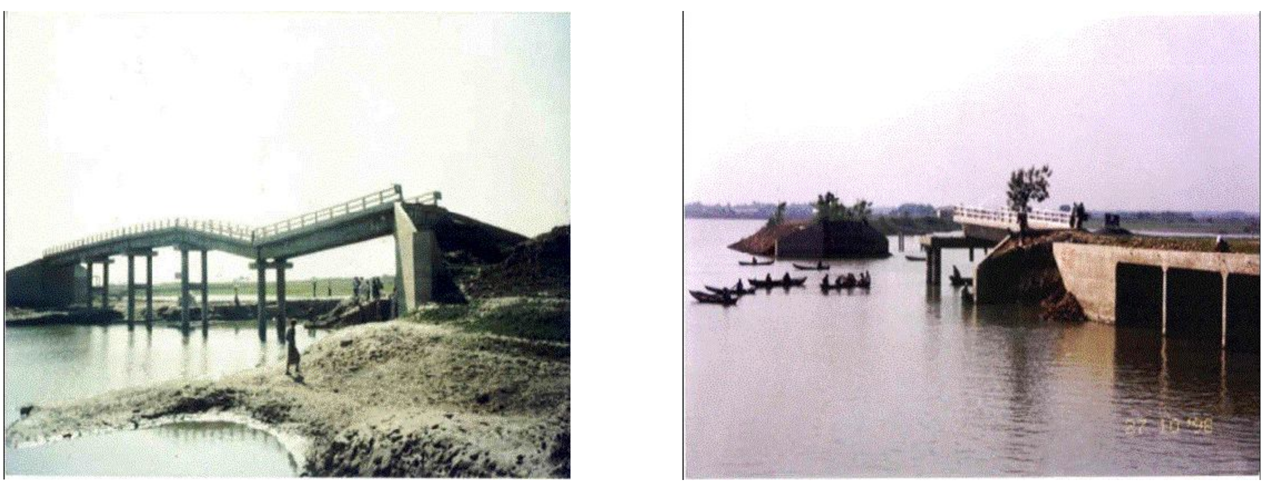
The 920 m long road bridge over river Karnaphuli, using previously used steel trusses donated by the Dutch government, was constructed during 1988-89. Just after two years of opening, on the night following 29th April, 1991, at around 3:05 am, a Category V super cyclone hit the coastal areas of Bangladesh with wind speed up to 225 kmph accompanied with storm surges up to 6m high. A 100-ton floating crane Shaktiman, which was anchored at the Chittagong port, was uprooted, moved a few kilometers upstream with the surge water and hit one of the suspended spans, removing the 100 m long steel trusses from their bearings (Figure 9a). The two trusses along with the timber decking were laid in river together with the sunken crane as shown in Figure 9(b). Some of the piles and members of the trusses also sustained minor damages (IEB Task Force Report 1991). The following year, the damaged parts of the bridge trusses were repaired, replaced and reconstructed.

(a) (b)

Figure 9. Image of bridge after the collapse (a) Part of Karnaphuli bridge (looking towards south), (b) Image of collapsed span along with the crane that hit the bridge. The undamaged part of the bridge is visible in the back.

4.3 *Turag-Bhakurta Bridge (1995 and 1998)*

The 67 m long Turag-Bhakurta Bridge was constructed by Local Government Engineering Department (LGED) in 1995. Just after completion of its construction work, the bridge experienced a flood in 1995 and as a result, the scour depth at pier-1 reached the pile length (6 m) which led to the settlement of the pier along with the adjacent deck and girder (Figure 10a). In 1998, the flood level reached the superstructure of the bridge level and created huge hydraulic pressure on the superstructure as well as substructure (Bala et al. 2005). Due to inadequacy of freeboard some of the girders were washed away with the water due to narrow flood water path as shown in Figure 10(b) (Bala et al. 2005).



(a) (b)

Figure 10. Failure of bridge near Amin Bazar (a) settlement of pier due to scour in 1995 flood, (b) complete collapse of bridge in 1998 flood (Bala et al. 2005)

5 CONCLUDING REMARKS

Although thousands of bridges are being constructed every year around the world, only few collapse due mainly to natural factors (flood, scour, earthquake, landslide, wind, etc.) and human factors (improper design and construction method, collision, overloading, fire, corrosion, lack of inspection and maintenance, etc.).

Some of these unfortunate incidents result not only in economic loss, but also in loss of human life. Bridge designers try to avoid failures by analyzing the causes of failures and learning from them. The development of new materials and new and more efficient forms of substructure and superstructure as well as new technology of construction, leading to longer spans, will obviously require a more careful consideration of some of the factors mentioned in this paper. It is the responsibility of the engineers and contractors to acquire the knowledge from every collapse and make sure the next bridge will be safer.

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