State-of-the-Art Review on the Causes and Mechanisms of Bridge Collapse

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Abstract: This paper is intended to review the main causes and mechanisms of bridge collapse. The common factors resulting in bridge collapse are first reviewed. These factors are classified into two broad categories, namely, natural factors (including flood, scour, earthquake, landslide, debris flow, hurricane, typhoon, wind, etc.) and human factors (including imperfect design and construction method, collision, vehicle overloading, fire, terrorist attack, lack of inspection and maintenance, etc.). Then the collapse modes of a few major types of bridges are reviewed and some relevant measures adopted in the current practices are discussed. It is hoped that this paper will provide a concise but comprehensive summary of information needed by researchers and engineers to understand the collapse mechanisms of the major bridge types and how the current practices deal with these issues. Meanwhile, much effort is made to identify future research needed to better understand this topic and to find better solutions to address the existing issues. **DOI: 10.1061/(ASCE)CF.1943-5509.0000731.**

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Introduction

Bridge collapse usually associates with serious economic and life losses (Estes and Frangopol 2001; LeBeau and Wadia-Fascetti 2007). For example, the failure of the Silver Bridge in Ohio in 1967 caused 46 deaths, and the more recent collapse of the I-35 W Bridge in Minnesota in 2007 killed 13 people and injured another 145 (Feldman 2010), and resulted in a direct economic loss of US$17 million in 2007 and US$43 million in 2008, respectively, excluding the huge indirect economic losses (Xie and Levinson 2011). During the period between 1989 and 2000, a total of 503 bridge collapses were reported in the United States, causing huge losses to the nation (Wardhana and Hadipriono 2003).

Throughout history, the causes and mechanisms of bridge collapse have drawn much attention from researchers and engineers, and much knowledge and design experience has been gained from the lessons of real bridge collapses. For instance, after the collapse of the original Tacoma Narrows Bridge in 1940, as shown in Fig. 1, much research effort was put into investigating the failure of this bridge and a physical phenomenon known as aeroelastic flutter was found to contribute to the bridge failure (Billah and Scanlan 1991). The failure of this bridge promoted research in the field of bridge aerodynamics-aeroelastics, which has influenced the design of long-span bridges since the 1940s.

In the past two decades, the advances of finite-element methods and computer technologies have provided useful tools for researchers to study bridge collapse on a numerical basis. Meanwhile, some experimental studies and field tests have also been conducted to better understand the collapse of bridges. Although much progress has been made on understanding the behavior and collapse of bridges, many challenging issues still remain. First of all, bridge collapse is usually a very complex process that results from a combined effect of many different factors. Therefore, it is sometimes difficult to identify the leading factor that has directly resulted in the collapse. Furthermore, it is difficult to perform field tests to study the collapse of bridges due to safety concerns and cost issues (Zhang et al. 2013; Piran Aghl et al. 2014). Meanwhile, collecting data from the site of bridge collapse is difficult because the site is usually severely damaged and cannot be recovered.

It is the aim of this paper to review and summarize some important findings on the causes and mechanisms of bridge collapse and to provide some suggestions for future research in this field. This paper is organized as follows: first, different causes of bridge collapse, which are classified into two broad categories, namely, natural factors and human factors, are reviewed; then, the collapse modes of different types of bridges are reviewed and the relevant measures adopted in current practices are discussed; finally, conclusions are drawn based on the findings and suggestions are provided for future research on this topic.

Causes of Bridge Collapse

Throughout history, many bridges collapsed due to different reasons. This paper classifies the main reasons for bridge collapse into two broad categories, namely, natural factors and human factors. According to an investigation by Wardhana and Hadipriono (2003), during the period between 1989 and 2000, a total of 503 bridge collapses were reported in the United States with the distribution of causes of these bridge collapses shown in Fig. 2. From Fig. 2 it can be observed that flood and scour together account for nearly half of the bridge collapses.

Natural Factors

Natural disasters, e.g., flood, scour, earthquake, landslide, debris flow, hurricane, and typhoon, are often unavoidable and can cause serious damages to bridges. The mechanisms of action on bridge

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Fig. 1. Collapse of the original Tacoma Narrows Bridge in 1940 (reprinted from WIKIPEDIA 1940)

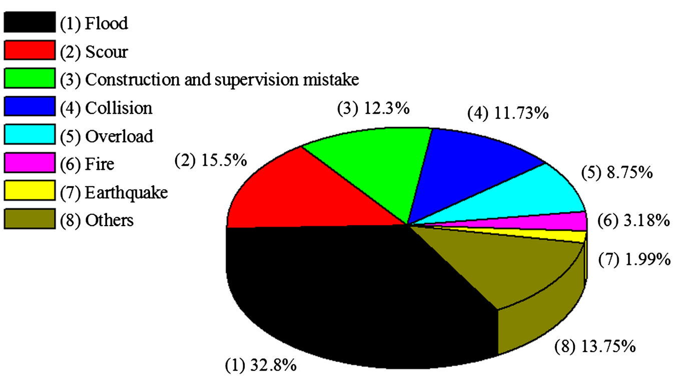

Fig. 2. Distribution of causes of the 503 reported bridge collapses during the period between 1989 and 2000 in the United States (data from Wardhana and Hadipriono 2003)

Fig. 3. Collapse of the Schoharie Creek Bridge due to flood in 1987 (reprinted from USGS 2012)

structures by different natural factors vary significantly and are summarized in the following sections.

Flood

Heavy precipitation usually leads to flooding, which may induce phenomena such as scour, erosion, river convergence, insufficient embedment depth, protection works-induced overfall or hydraulic jump, softened bedrock, sand mining, debris impact or abrasion on bridge foundations, etc. (Witzany et al. 2008; Hong et al. 2012; Wang et al. 2014a). One or a combination of these causes can result in dramatic reductions in the strength and stability of bridge key components and can even cause bridge failures, as shown in Fig. 3.

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 (AASHTO 2012). 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 (Daniels et al. 2007; Lin et al. 2010). Furthermore, when the critical scour depth is reached, bending buckling of the foundation may occur under the combined effect of the dead load of bridge superstructures and the traffic load (Walton et al. 1982; Hughes et al. 2007).

Earthquake

Earthquakes lead to vertical and horizontal ground motions that can result in the failure of bridge substructures (Yang and Lee 2007; Warn and Whittaker 2008; Wang et al. 2013). The vertical ground motion causes significant fluctuating axial forces in bridge columns or piers, which may induce outward buckling or crushing of the columns or piers (Kunnath et al. 2008; Kim et al. 2011). Moreover, the vertical ground motion can result in significant amplification of the bending moment at the bridge midspan, which may lead to the bending failure of the bridge deck (Veletzos et al. 2006; Kunnath et al. 2008). Unlike the vertical ground motion, the horizontal ground motion mainly contributes to the shear failure of bridge columns or piers (Priestley et al. 1994; Sun et al. 2012). 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 and even directly lead to bridge collapse (Hashimoto and Chouw 2003; Wang et al. 2013).

Landslide

The occurrence of a landslide is 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 (Varnes 1984; Iverson 2000). These moving slope-forming materials, when hitting the bridge, will lead to severe damage or even collapse of the bridge, as shown in Fig. 4.

Debris Flow

A debris flow is usually translated from a landslide when water is incorporated into the landslide debris as it is jostled and remolded during the downslope movement. Remolding and incorporation of water reduce the strength of the debris and make it behave like a fluid, causing it to flow rather than slide (Hampton 1972; Takahashi 1978). A debris flow exerts tremendous impact forces on the obstacles in its way, especially when large stones are transported. Moreover, a growing debris flow has severely erosive effects. Therefore, when a large-scale debris flow passes the site of a bridge, the damage to the bridge could be devastating (Takahashi 1978, 1991).

Fig. 4. Collapse of a bridge due to landslide (image courtesy of Xi Zhang)

Hurricane and Typhoon

Hurricanes and typhoons are tropical cyclones that refer to low pressure systems that generally form in the tropics. They travel with wind waves accompanied by storm surges, which raise the water level to an elevation that is able to strike the superstructure of bridges along the coast. Bridge decks may be knocked off the pile caps by the impulsive vertical and horizontal forces generated by the storm waves riding on high surges (Robertson et al. 2007; Chen et al. 2009a), as illustrated in Fig. 5. Moreover, after making their landfall, hurricanes usually lead to heavy rainfalls and cause a series of subsequent disasters such as flood, landside, and debris flow (Hong et al. 2012; Wang et al. 2014a).

Wind

Wind could induce aerostatic and aerodynamic instability problems for flexible long-span bridges. Aerostatic instability can be categorized into two types according to the modes of static instability, namely, torsional divergence and lateral-torsional buckling (Boonyapinyo et al. 1994; Cheng et al. 2002). Aerodynamic vibration is usually caused by three different types of oscillations, namely, flutter, buffeting, and vortex-induced oscillation (Scanlan 1998; Ge and Tanaka 2000). Both aerostatic and aerodynamic forces may lead to large displacements and stresses that may exceed the capacity of bridge structures such as decks and cables, resulting in the collapse of bridges (Scanlan 1998; Cheng et al. 2002).

Fig. 5. Bridge decks knocked off pile caps during hurricane (image courtesy of Wikimedia Commons/Joe Furr, WIKIPEDIA 2005)

Human Factors

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

Imperfect Design and Construction Method

In many cases, errors stemming from an imperfect design, willful use of inferior materials, or adoption of an inappropriate construction method can lead to bridge collapse in the construction phase (Abdelhamid and Everett 2000; Mitropoulos et al. 2005). For example, 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.

Collision

Accidental collisions between vehicles and bridge superstructures and between vessels and bridge piers or columns can be unpredictable. During the collision, very large lateral forces are transmitted to the impacted bridge structures (Consolazio and Cowan 2005; Fan et al. 2011). This large impact force, acting on a relative small contact area, can cause very high local pressure and therefore local damage to bridge components. Furthermore, as the bridge absorbs the dynamic collision energy, significant inertial forces and vibrations will be developed. Collision forces can, therefore, lead to severe damage to bridge components or even collapse of the bridge (Davidson et al. 2013; Xia et al. 2014).

Vehicle Overloading

Due to the increasing competition in the transportation market, vehicle overloading has become more and more common and has raised serious concerns around the world (Fu and Hag-Elsafi 2000). 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 even exceed the load-carrying capacity of the bridge and directly cause bridge collapse, as shown in Fig. 6.

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; Payá-Zaforteza and Garlock 2012). Fire can reach very high 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; Payá-Zaforteza and Garlock 2012). 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

Fig. 6. Bridge collapse due to an overloaded truck (image courtesy of Yuqiang Liu)

and stiffness of materials, which can further lead to partial or full collapse of bridges (Bai et al. 2006; Astaneh-Asl et al. 2009).

Terrorist Attack

Recent years have witnessed a number of terrorist attacks against transportation systems worldwide (Jenkins 2001). Transportation infrastructures have been considered as attractive targets for attack because of their accessibility and potential impacts on human lives and economic activities (Yi et al. 2013). Terrorist attacks usually aim at key bridge components such as bridge piers and decks, the failure of which usually results in the dysfunction or collapse of bridges (Winget et al. 2005; Wang et al. 2014c).

Lack of Inspection and Maintenance

Bridges in service are constantly subject to attack by the environment and live loads. 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 and mechanical and environmental stressors (Kong and Frangopol 2005; Kim et al. 2013). Though the risk of bridge failures cannot be completely eliminated, a good maintenance program including regular inspection and proper rehabilitation will slow down the deterioration process of bridges and help detect potential structural problems before they develop into serious disasters (Estes and Frangopol 2001; Biezma and Schanack 2007).

Collapse Mechanisms of Bridges

In this section, the collapse mechanisms of a few common bridge types, namely, beam bridges, arch bridges, steel truss bridges, and flexible long-span bridges, will be reviewed. The common failure modes for each type of bridge will also be discussed.

Beam Bridges

Beam bridges are the simplest and most common bridge type among all bridges. Beam bridges account for roughly half of all bridges in the United States, while the percentage of beam bridges reaches 74% in China (Li 2011). In the following sections, six main causes for the failure of beam bridges, namely, flood and scour, collision, vehicle overloading, earthquake, blast, and hurricane, will be reviewed and discussed separately.

Flood and Scour

Flood and scour account for nearly half of all bridge failures (Wardhana and Hadipriono 2003). Bridge scour generally includes four main types, namely, local scour, contraction scour, general scour, and channel migration, and can be seriously exacerbated by flood. Based on a review of the failure of 36 bridges by Lin et al. (2014), the failure modes of bridges caused by bridge scour can be categorized into four main types: vertical failure, lateral failure, torsional failure, and bridge deck failure. Vertical failure of bridges caused by scour could be attributed to a combination of factors such as inadequate soil support and pile instability and can be generalized into four categories: inadequate bearing capacity of shallow foundations, penetration of friction piles, undermining of pile toes, and pile buckling, as illustrated in Fig. 7 (Lin et al. 2014). Lateral failure usually occurs in one of the following forms: push-over failure of piers, formation of structural hinges in piles, kick-out failure of foundations, and excessive lateral movement of piers or foundations. Torsional failure refers to the failure of structures or structural components attacked by skewed flows. Bridge deck failure, usually in the form of deck unseating, may occur when the flood-induced external force is sufficiently large to overcome the gravity force of the bridge deck and the restraint forces from the support.

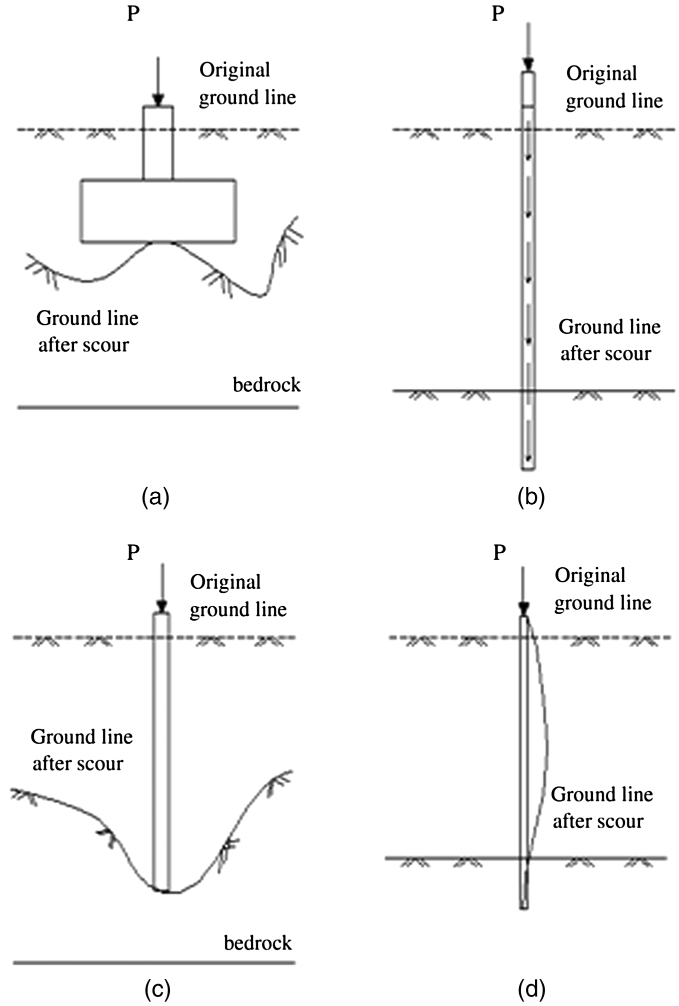

Fig. 7. Vertical failure modes of bridge foundations: (a) undermining of footing base; (b) penetration of friction pile; (c) undermining of pile tip; (d) buckling of pile (reprinted from Lin et al. 2014, © ASCE)

The AASHTO LRFD code (AASHTO 2012) requires that bridge foundations be designed to withstand the conditions of scour for both the design flood and the check flood. A comprehensive review of the countermeasures for bridge scour can be found in

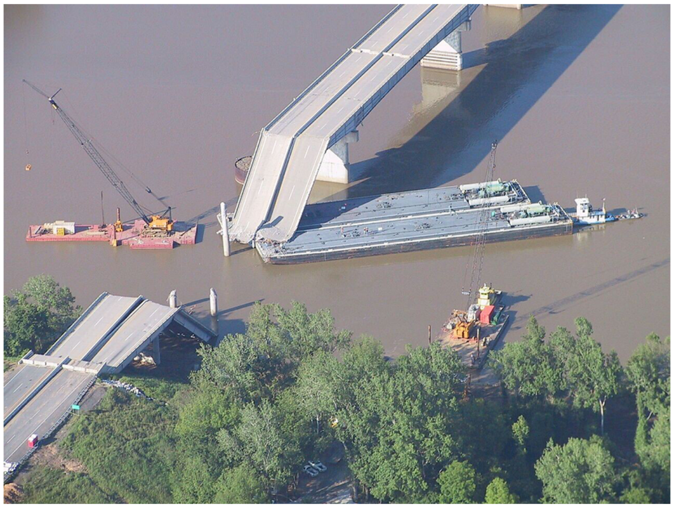

Fig. 8. Collapse of a bridge due to vessel impact (image courtesy of Wikimedia Commons/Xpda, WIKIPEDIA 2002)

Deng and Cai (2010). Although many countermeasures are available, it is suggested that the actual scour condition of a specific bridge site should be fully investigated before appropriate countermeasures are taken to reduce the potential damage due to scour.

Collision

Studies have been conducted to investigate the behavior of beam bridges subjected to vessel impacts (Fan et al. 2011; Madurapperuma and Wijeyewickrema 2013), rock impacts (Lu and Zhang 2012; Piran Aghl et al. 2014), and vehicle collisions (El-Tawil et al. 2005; Xu et al. 2013). Collision can not only cause serious damage to local structural components but also lead to progressive collapse of multispan bridges. A number of progressive bridge collapses initiated by the failure of local structural components caused by collision have been reported (Knott 1998; Yuan 2005). In order to prevent progressive collapse, researchers have studied the mechanisms of bridge progressive collapse due to the accidental loss of supports for beam bridges. For example, Lu and Zhang (2013) studied the failure process of the Jiujiang Bridge 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. Fig. 8 shows a picture of the collapse of a bridge due to vessel impact. Ghali and Tadros (1997) investigated the progressive collapse mechanism of the Confederation Bridge crossing the Northumberland Strait based on analytical and experimental studies and suggested that connecting the adjacent spans of continuous beam bridges by hinges at the expansion joints will prevent the progressive collapse of the bridge.

In the AASHTO LRFD code (AASHTO 2012) the impact load on a bridge pier due to ship collision is included in the design loads, which shall be calculated as

$$P_s = 0.556V\sqrt{\mathrm{DWT}} \tag{1}$$

where P_s= equivalent static vessel impact force (kN); DWT = deadweight tonnage of vessel (metric tons); and V = vessel impact velocity (m/s). It can be seen from Eq. (1) that accurate estimation of the maximum possible velocity and deadweight tonnage of vessels is of great importance to obtain the correct design impact load due to ship collisions. To account for vehicle collision, the AASHTO (2012) code requires that the abutments and piers located within a distance of 9.144 m (30.0 ft) to the edge of roadway shall be designed for an equivalent static force of 2,669 kN (600 kips), 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 1.542 m (5.0 ft) above the ground.

Vehicle Overloading

Vehicle overloading has become progressively more common with increasing traffic demand. Vehicle overloading can accelerate the deterioration of pavement, reduce the fatigue life of bridge components, and can even cause sudden bridge collapse under some extreme cases. Overload-induced bridge collapse is most likely to occur in beam bridges and slab bridges, as the traffic load accounts for a significant portion of the total load on these bridges while this is not the case for long-span bridges. Performing destructive tests on real in-service bridges provides a straightforward and effective way to understand the overload-induced failure mode of bridges but can be very expensive and difficult to realize. Testing on decommissioned bridges has been used as an alternative by many researchers. Three main failure modes of bridge decks have been found: shear failure mode (Bergström et al. 2009), flexural failure mode (Zhang et al. 2013), and plastic failure mode (Wang et al. 2011). In addition, the failure modes of skewed beam bridges due to vehicle overloading were also studied and similar failure modes have been obtained (Helba and Kennedy 1994; Ebeido and Kennedy 1996; Bechtel et al. 2009). However, it should be noted that the ultimate capacity of a skewed bridge decreases significantly with an increase in the skew angle, especially when the skew angle is greater than 30°. It should also be noted that the exterior girder tends to shoulder more load and thus fail with the increase of the skew angle (Ebeido and Kennedy 1996).

Enforcement of vehicle weight regulations is an effective way to reduce the overload-induced fatigue damage and collapse of bridges. Those setting proper weight limits for a bridge should consider a series of factors, among which the most important ones are the target reliability, the load-carrying capacity of the bridge in consideration, and the characteristics of the traffic. In the United States, the maximum weight limitations for a single axle and axle group are 89 kN and 151 kN, respectively, and the limitation for the gross vehicle weight is 356 kN (Walton et al. 1982). Current research on bridge weight limitation is based on analysis using the reliability theory (James et al. 1986; Ghosn 2000; Kim 2012), which takes into consideration the uncertainties of the bridge resistance and vehicle load effects.

Earthquake

Ground shaking and rupture, which are the main effects created by earthquakes, can have significant impacts on the stability and safety of infrastructure, including bridges. Much research has been conducted to investigate the seismic-induced failures of beam bridges and the results showed that bridge decks, bearings, and supports (including abutments, piles, and columns) are the most vulnerable parts of bridges under the effect of earthquakes. The decks of simply-supported bridges, either single-span or multispan, can fall off or slide away from the abutments or columns due to large horizontal ground movements (Siddharthan et al. 1997; Saadeghvaziri and Yazdani-Motlagh 2008; He et al. 2012). The horizontal ground movement can also lead to impact between adjacent spans and between the end-span and the abutment, which may result in the following problems for simply-supported bridges: failure of rocker bearings in the form of toppling (Nielson and DesRoches 2006), shear failure of the steel bearings (Pan et al. 2010), and failure of abutment backwalls (DesRoches et al. 2004; Saadeghvaziri and Yazdani-Motlagh 2008). It is worth noting that the oblique impact on skewed reinforced concrete bridges tends to make the bridge rotate in the horizontal plane and drop off the supports at the acute corners (Hall et al. 1996; Dimitrakopoulos 2010). Due to the seismic effect, bridge columns or piers tend to fail in three modes, namely, flexural failure (Priestley 1988; Lou and Zerva 2005; Bhattacharya et al. 2008), shear failure (Ghobarah and Ali 1988; Hwang et al. 2000), and crushing failure (Papazoglou and Elnashai 1996; Kim et al. 2011).

Different techniques have been studied and developed to prevent and reduce seismic-induced bridge failures, such as seismic isolation, inelastic hinges, etc. To reduce the risk of the deck falling off, which has been found to be a typical failure mode of beam bridges due to insufficient support lengths, the AASHTO LRFD code (AASHTO 2012) states that the minimum empirical support length shall be taken as

$$N = 0.121X(8 + 0.02L + 0.08H)(1 + 0.000125S^2) \qquad (2)$$

where N = minimum support length measured normal to the centerline of the bearing (cm); L = length of the bridge deck to the adjacent expansion joint, or to the end of the bridge deck (m); H = height of the column or pier (m); and S = skewness of the support measured from the line normal to the span (degrees). Besides, the AASHTO code (AASHTO 2012) states that in the design and detailing of bearing components that resist large lateral loads due to earthquakes and other extreme events adequate strength and ductility should be provided. Moreover, the AASHTO code (AASHTO 2012) specifies that inelastic hinges shall be ascertained to form in columns before any other failure occurs due to overstress or instability in the structure and/or in the foundation. Inelastic hinges shall only be permitted at locations in columns where they can be readily inspected and/or repaired.

In recent years, the displacement-based design method has gained popularity and has been widely believed to be more reasonable than the traditional force-based method. The displacement-based design philosophy requires that a bridge be designed to have adequate displacement capacity to accommodate earthquake demands. The AASHTO code (AASHTO 2012) recommends that the displacement capacity of bridges be designed in accordance with force-based specifications and be checked using a displacement-based procedure, particularly for those bridges in high seismic zones.

Blast

With the increase in terrorist attacks in recent years, the safety of critical bridges under blast loading has become a public concern and a topic of interest for many researchers. Yi et al. (2014) conducted a comprehensive series of simulations on the blast effects on three-span simply-supported highway bridges and suggested the following failure mechanisms for the important bridge components: (1) pier: eroding of pier bottom concrete, shearing of a pier from the footing, rebar severance, breakage of pier, spalling of concrete surface, and formation of plastic hinges; (2) bent beam: local failure of concrete underbearings, crushing of concrete, and shear failure; (3) stringer: collapse, and yielding of the steel; (4) deck: crushing under high pressure, dislocation under the effect of the blast wave, and collapse due to loss of support. They also suggested that not all failure mechanisms may appear during the blast for a particular bridge. The presence of a particular failure mechanism depends on many factors, including the bridge geometry, magnitude of blast loads, standoff distance, the surrounding environment, etc. However, all major mechanisms may be present under high-level blast loads, and the bridge can be damaged completely. It should also be noted that progressive collapse may occur under the effect of a blast, as demonstrated in the failure of a multispan bridge on the Northumberland Strait in Canada due to the loss of a local bridge component during a blast event (Ghali and Tadros 1997).

For bridges or structural components that need to be designed for intentional or unintentional blast loads, the AASHTO code (AASHTO 2012) suggests that the following should be considered: (1) the size of explosive charge; (2) the shape of explosive charge; (3) the type of explosive; (4) the standoff distance; (5) the location of the charge; (6) the possible modes of delivery and associated capacities; and (7) the fragmentation associated with vehicle-delivered explosives. However, as the size of the explosive charge is unpredictable, the cost of building bridges capable of resisting all possible potential blasts would be very high.

Hurricane

Coastal bridges are prone to attack by hurricanes (Okeil and Cai 2008). The performance of coastal bridges under hurricanes has drawn increasing attention after the collapse of a large number of bridges during the last decades. Deck unseating (Fig. 5) has been found to be the predominant failure mode for simply-supported multispan coastal bridges without supplemental restraints (such as shear keys) during hurricane events (Padgett et al. 2008; Chen et al. 2009a; Ataei and Padgett 2013). Deck unseating could result once the uplift force from the wave and air trapped underneath the bridge deck overcomes the gravity load of the bridge deck and the restraint forces from the supports are not sufficient to resist the lateral wave forces. Padgett et al. (2008) also pointed out that the impact of barges, oil drilling platforms, tug boats, and other types of debris could also result in damage in the form of span misalignment and damages in fascia girders, fenders, and piles. Another failure mode for bridges during hurricanes is scour damage, including scour and erosion of abutments, slope failure, and undermining of approach spans.

Based on the observed failure modes of bridges due to hurricanes, it is obvious that the connections between the bridge deck and piles or abutments play an important role in standing hurricane-induced wave loads, and that they should therefore be reinforced for bridges built in hurricane-prone zones (Xu and Cai 2014). Recently, some numerical models have been developed to estimate wave loads on bridge superstructures and to study bridge failure modes under the effect of hurricane-induced wave loads (Chen et al. 2009a; Huang and Xiao 2009; Xiao et al. 2010; Jin and Meng 2011). Nevertheless, no formulas have yet been provided for estimating wave loads in the AASHTO code (AASHTO 2012).

Arch Bridges

Much research has been conducted to study the failure mechanism of masonry arch bridges. Heyman (1982) established a four-hinge collapse mechanism, shown in Fig. 9(a), to determine the load limit that can be applied at the quarter-span of a masonry arch bridge based on three assumptions: (1) the masonry in the arch has no tensile strength; (2) the masonry in the arch is incompressible; and (3) sliding between masonry units is not allowed. The author also pointed out that under the effect of support settlement, three hinges would be developed before the collapse of the arch, which was also validated by Drosopoulos et al. (2006). However, Drosopoulos et al. (2006) also found that though deep arches fail following the four-hinge collapse mechanism, compressive failure usually arises in shallow arches. Similar results were observed by Brencich and De Francesco (2004) and Riveiro et al. (2011). Clemente et al. (1995) extended Heyman's theory and further concluded that the collapse mechanism of bridges with symmetric structural geometry under symmetric loading must be symmetric. Therefore, there must be at least five hinges when failure occurs under such loading scenarios, one of them being at the crown.

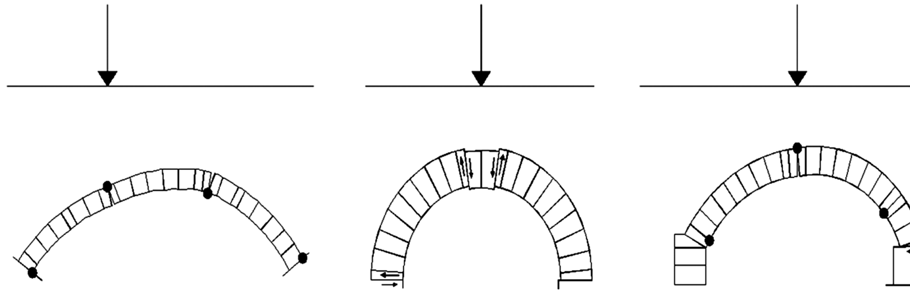

Fig. 9. Collapse mechanisms of stone arch bridges (data from Gilbert 2007)

In addition, the sliding failure mode of stone arch bridges, as shown in Fig. 9(b), was also supported by many researchers (Livesley 1992; Baggio and Trovalusci 1998; Gilbert 2007; Orduña and Lourenço 2005). LimitState (2007) proposed a combined failure mode with hinges and sliding, as shown in Fig. 9(c). Moreover, the progressive collapse of multispan arch bridges has drawn the attention of many researchers due to its frequent occurrence (Farrar and Jauregui 1998; LeBeau and Wadia-Fascetti 2007; Xu et al. 2013). The unbalanced force resulting from the local failure of a key structural component in one span could lead to the subsequent failure of adjacent spans and eventually the collapse of the entire bridge (Starossek 2007). Fig. 10 shows a picture of the progressive collapse of a stone arch bridge in China.

In addition to research on stone arch bridges, much research has been conducted to investigate the failure mechanisms of steel arch bridges, which can be categorized into three main types: in-plane, out-of-plane, and spatial failure modes. Yabuki et al. (1983) studied the effect of out-of-plane rigidity on the ultimate behavior of steel arch bridges and found that bridges with insufficient out-of-plane rigidity showed a tendency to have fairly large out-of-plane as well as in-plane displacements with an increase in vertical load, which would result in spatial collapse. Cheng et al. (2003) investigated the failure modes of a long-span steel arch bridge under the combined action of dead load and wind load. It was found that when the wind load was small, the bridge had fairly large in-plane displacement and small out-of-plane displacement, resulting in the in-plane collapse of the bridge. However, when the wind load was sufficiently large, the bridge had both fairly large in-plane and out-of-plane displacements, leading to the spatial collapse of the bridge.

In the design of a steel arch bridge, the AASHTO LRFD code (AASHTO 2012) requires that the effect of the extension of cable hangers shall be considered in the analysis of an arch tie to take into account the composite action with the deck or deck system. In addition, arches with longer spans should be considered based on the large deflection analysis.

Steel Truss Bridge

Studies have shown that the failure of a steel truss bridge could usually be triggered by the failure of a critical structural member or connection, which can be an eyebar, a vertical member, a gusset plate, etc. (Lee 1996). Lee (1996) studied the failure of the Sungsoo Grand Bridge across the Han River in Seoul, Korea, and concluded that the fracture of a vertical structural member and the consequential pulling out of the suspended truss caused the collapse of the bridge. Investigation of the collapse of the I-35 W Bridge in Minnesota, as shown in Fig. 11, by different researchers has shown that the collapse of the bridge was initiated by the failure of the gusset plate U10, which then led to the progressive collapse of the main truss in a brittle manner due to the lack of redundancy in the truss (Astaneh-Asl 2008; Ocel et al. 2010; Hao 2010). It is therefore very important for steel truss bridges to have a sufficient level of structural redundancy.

In addition, establishing and maintaining a regular program of maintenance is also very important to assure both the safety and serviceability of steel truss bridges. Azizinamini (2002) conducted full-scale testing on an old steel truss bridge. Two conditions were investigated for this bridge, namely, its existing condition without any retrofit and a condition in which the failed member together with other forged tension members were retrofitted. Azizinamini

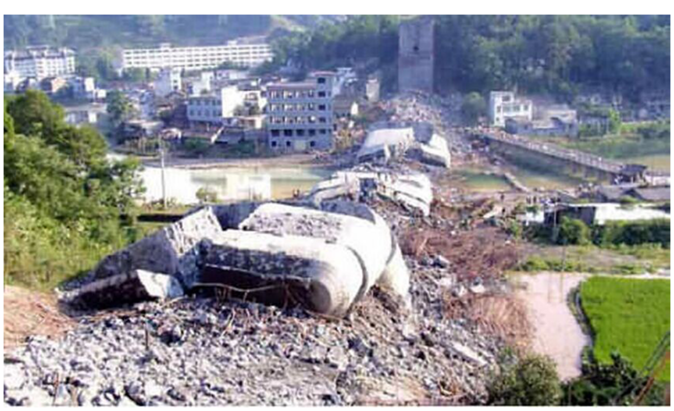

Fig. 10. Progressive collapse of a stone arch bridge in China (image courtesy of Yafang Zhu)

Fig. 11. Collapse of the I-35 W Bridge in Minnesota in 2007 (image courtesy of Wikimedia Commons/Mike Willis, WIKIPEDIA 2007)

found that in the former condition the failure was initiated by the sudden rupture of a forged diagonal tension member while the failure under the latter condition took place gradually and there was obvious warning before the failure.

In the AASHTO LRFD code (AASHTO 2012) a refined plane or space frame analysis of a steel truss bridge shall include consideration of the following: (1) the composite action between the frame and the deck or deck system; (2) the continuity among different components; (3) the force effects due to the self-weight of components, change in geometry due to deformation, and axial offset at panel points; and (4) the in-plane and out-of-plane buckling of components.

Flexible Long-Span Bridges

The stability of flexible long-span bridges, such as cable-stayed and suspension bridges, has been a research topic of interest among many researchers. The stability of flexible long-span bridges usually involves three basic aspects, namely, static stability, aerostatic stability, and aerodynamic stability.

Static Stability

Static stability is an important issue that needs to be addressed when designing a flexible long-span bridge. A static stability analysis usually involves the analysis of the behavior of cables, pylons, and bridge decks under the expected loading condition; nonlinear analysis methods are usually adopted. Yoo et al. (2012) proposed a new nonlinear inelastic analysis approach to estimating the ultimate capacity of a steel cable-stayed bridge and concluded that the buckling of the pylon or deck or the yielding of cables could lead to the collapse of the bridge. Song and Kim (2007) analyzed the in-plane collapse mechanism of steel cable-stayed bridges with different cable layouts under static loads based on the bifurcation point instability approach and the limit point instability approach. They found that the plastic hinges first developed at the midspan of the bridge deck initiated the overall collapse of the bridge. Ren (1999) investigated the nonlinear static and ultimate behavior of a long-span cable-stayed bridge and found that local buckling of the slender steel girder could result in the overall failure of the bridge.

Aerostatic Stability

The study of aerostatic stability addresses two main issues, namely, torsional divergence and lateral-torsional buckling (Boonyapinyo et al. 1994). The phenomenon of torsional divergence is characterized by a monotonically increasing rotation at a critical wind velocity at which the overturning pitching moment eventually exceeds the elastic torsional resistance of the bridge structure. Like most instability problems, torsional divergence occurs abruptly at the critical wind velocity and can cause a bridge to collapse (Xu 2013). On the other hand, lateral-torsional buckling is characterized by the combination of vertical buckling and twisting of the deck at a critical wind velocity. At this wind velocity, the three components of the wind forces (drag force, lift force, and pitching moment), together with axial forces in the deck and tower induced by their own dead loads, reduce the effective stiffness of the bridge to zero, leading to the collapse of the bridge (Boonyapinyo et al. 1994). Boonyapinyo et al. (2006) also found that nonlinear aerostatic instability can occur before the occurrence of flutter based on the study of the nonlinear aerostatic stability of long-span suspension bridges when taking bridge geometric and material nonlinearities into consideration.

Aerodynamic Stability

The three classic aerodynamic problems of flexible long-span bridges are flutter, buffeting, and vortex-induced oscillation (Billah and Scanlan 1991; Cai et al. 1999; Chen et al. 2000). Flutter is an oscillatory instability problem that occurs in the bridge deck at the critical wind velocity (Scanlan 1997; Ge et al. 2000; Ge and Tanaka 2000). Unlike flutter, buffeting is the random response of a bridge due to turbulence in the oncoming wind flow, or due to signature or self-induced turbulence (Xu et al. 1998; Nguyen Minh et al. 1999; Chen et al. 2009b), while vortex-induced oscillations can be induced by cross winds at relatively low velocity (Ehsan and Scanlan 1990; Chen et al. 1995; Li et al. 2011).

Flutter is a self-feeding and potentially destructive vibration to a flexible long-span bridge when the aerodynamic forces on the bridge deck couple with the deck motion. If the energy input by the aerodynamic force in a cycle exceeds the energy that can be dissipated by damping in the bridge system, the vibration amplitude of the bridge deck will increase. This increasing vibration will in turn amplify the aerodynamic force, which again amplifies the vibration of the bridge deck until the bridge collapses (Xu 2013). One famous example of bridge failure due to flutter was the collapse of the original Tacoma Narrows Bridge in 1940, as illustrated in Fig. 1.

Buffeting is caused by the turbulence or gustiness in the natural wind, which produces fluctuating forces on a flexible long-span bridge. The wind velocity, wind-induced force, and the consequent bridge response are usually random in nature. The magnitude of the fluctuating wind force is a function of the intensity of the turbulence and its length scale (Kareem 2013). The turbulence intensity determines the magnitude of the local fluctuation forces while the turbulence length scale, which is related to the size of the bridge, determines how well the fluctuations are correlated over the bridge. Although a buffeting response does not generally lead to catastrophic failure, a large buffeting response may cause fatigue problems at bridge joints and discomfort to users, and may even affect bridge safety (Nguyen Minh et al. 1999).

Vortex-induced vibration is triggered by the shedding of vortices from the surface of the bridge deck when a flexible long-span bridge is immersed in a wind flow. These vortices provide a periodic excitation to the bridge deck and cause it to vibrate. Usually, this vortex-induced oscillation is not significant except when the shedding frequency is close to the natural frequencies of the bridge. Although such oscillations usually do not cause catastrophic disasters, sustained oscillations at relatively low cross-wind velocities may cause fatigue problems in bridges (Ehsan and Scanlan 1990; Li et al. 2011).

Previous research has shown that the stiffness and profile of the bridge deck are two key factors that affect the aerodynamic behavior of long-span bridges (Zhang and Sun 2004; Wang et al. 2014b). Sufficient stiffness of the bridge deck can effectively dissipate the energy input by aerodynamic force from strong winds and can thus increase the critical wind velocity of flutter, while proper design of the bridge deck configuration can effectively control the shedding of vortices from its surface and can thus reduce the vortex-induced vibration. Nonetheless, due to the complexity of fluid-structure interactions, application of new light materials, and lack of knowledge in some important parameters for wind-resistant design, harmful vibrations caused by wind, such as vortex-induced vibrations, still develop in some circumstances. Such vibrations have been reported on the Volga River Bridge in Russia and other bridges.

Blast

The behavior of flexible long-span bridges under blast loading has also been investigated by many researchers. Hao and Tang (2010) and Tang and Hao (2010) performed intensive numerical simulations to investigate the dynamic responses and resulting damages of a cable-stayed bridge due to blast loading. They concluded that

Table 1. Most Common Causes for Collapse of Different Types of Bridges

Type of bridge	Most vulnerable causes
Beam bridge	Flood, scour, earthquake, collision, overloading
Masonry arch bridge	Flood, scour, overloading, earthquake
Steel arch bridge	Overloading, wind
Steel truss bridge	Overloading, fatigue
Flexible long-span bridge	Wind

when the explosion occurs near the towers and piers, the damage to the bridge is mainly induced by the resulting stress wave propagation, and local concrete crushing and spalling are the two main damage modes. By contrast, when the explosion was set away from the bridge, global damage modes (shear and flexural) may result. Therefore more significant damage to the bridge towers and piers may result although the scaled distance is larger. Moreover, catastrophic bridge collapse can be expected if damage to an entire cross section of towers and piers takes place. Son and Astaneh-Asl (2009) studied the blast-induced response of the orthotropic steel decks of cable-stayed and suspension bridges and pointed out that the collapse mode of orthotropic steel decks was in the form of buckling in the longitudinal direction due to the P-Δ effect. The axial compressive force P in the deck acting on the downward displacement Δ generated by the blast pressure caused this destabilizing P-Δ effect. Suthar (2007) investigated the effect of the combination of dead, live, and blast loads on a suspension bridge. Based on the bending moments and deformations of the structural members, the author concluded that although the suspension bridge experienced severe localized damage resulting from the blast load, collapse of the suspension bridge was unlikely for all the blast events considered.

Concluding Remarks

In this paper, a concise but comprehensive review of the causes and mechanisms of bridge collapse is presented. On the basis of the main findings, the following conclusions can be drawn:

1. Different types of bridges are vulnerable and sensitive to different causes, which have been summarized in Table 1.
2. The failure modes of beam bridges mainly include (1) bridge deck misalignment and falling off the abutments or columns due to inadequate support length of bridge decks or weak connections with supports; (2) bridge deck failure in the form of shear, crushing, and flexural failures; (3) bearings dysfunction in the form of shear failure or toppling; (4) pier and column failures in the form of shear, crushing, and erosion; and (5) progressive collapse due to unbalanced forces resulting from the loss of supports.
3. The failure mechanisms of masonry arch bridges include the four-hinge or five-hinge collapse, sliding failure, a combination of the hinge and sliding failure modes, and progressive collapse. Unlike masonry arch bridges, the failure mechanisms of steel arch bridges include in-plane, out-of-plane, and spatial failure modes, which are dependent on in-plane and out-of-plane rigidities. Excessive in-plane rigidity will result in out-of-plane failure modes and vice versa. Therefore, it is important to balance the in-plane and out-of-plane rigidities of such bridges in order for the collapse to occur in the form of spatial failure modes so that the in-plane and out-of-plane rigidities can be effectively utilized.
4. The collapses of steel truss bridges are mainly initiated by the failure of key bridge components such as connections and joints. Thus, it is critical for such bridges to have sufficient levels of redundancy to reduce the probability of collapse. In addition, establishing and maintaining a regular program of inspection and maintenance is also important to assure both the safety and serviceability of steel truss bridges.
5. Generally speaking, the stability of flexible long-span bridges involves three basic issues, namely, static stability, aerostatic stability, and aerodynamic stability. Both aerostatic instability (including torsional divergence and lateral-torsional buckling) and aerodynamic instability (including flutter, buffeting, and vortex-induced vibration) may result in tremendous displacements or stresses that exceed the capacities of the bridge structures. In addition, aerostatic instability is likely to occur prior to aerodynamic instability as the bridge span increases. Moreover, the stiffness and profile of flexible long-span bridges are two important factors that determine the aerostatic and aerodynamic stability of such bridges. Therefore, the optimization of these two parameters during the design is crucial to eliminate or avoid such wind-induced problems.

Based on a review of the advances achieved in this field, the following problems are identified and corresponding suggestions are tentatively made regarding future research:

1. Scour is a major cause for bridge collapse. However, available methods and technologies, based on either empirical equations or simple analytical and numerical models, fail to provide reliable predictions of the scour depth. More refined and capable three-dimensional numerical models could be very useful to help better understand and predict the development of scour. Meanwhile, technologies that can monitor real-time scour depth and provide reliable alarming should be developed in addition to developing good countermeasures that suit specific site characteristics.
2. Experimental data on bridge collisions are lacking, especially for vessel collisions. Previous research in this area may have underestimated the effect of inertia on bridge responses during the collisions. More refined numerical models should be developed to investigate the interaction between the bridges and vehicles/vessels.
3. Weight limitation is an effective way to reduce vehicle overloading-induced problems. However, how to set proper weight limitations to balance concerns of the public and government agencies over the deteriorating state of bridge structures and increasing demand from the trucking industry is in debate. To address this problem, methods and technologies that can provide better estimations of the loading-carrying capacity of existing bridges are desired.
4. More research is needed to analyze wave-structure interaction and to predict wave loads on bridge superstructures during natural disasters such as hurricane events. Formulas for estimating wave loads on bridges need to be proposed for safe design and capacity evaluation of coastal bridges.
5. Current experimental studies on bridge behaviors under seismic loads are subjected to many limitations due to experiment condition, size effect, multidimensional loading effect, etc. More studies are needed to analyze the complicated compression-bending-shearing-torsional coupling effect in bridge components. Furthermore, when analyzing the seismic behavior of bridges, especially long-span bridges, attention should be paid to the spatial dynamic effect of bridges while taking into consideration the effects of the traveling wave effect, the partial coherency effect, the wave attenuation effect, and the locality effect.
6. Current models that describe the interaction of two adjacent blocks of arch masonry bridges do not provide reliable

predictions of bridge responses. The Coulomb friction model may underestimate the tangential displacement between the two adjacent blocks while the associative friction model may overestimate the normal displacement between two adjacent blocks. A model that can better describe the behavior of two adjacent blocks of arch masonry bridges while considering the effect of dilatancy accompanying sliding is desired.

7. The complexity of fluid-structure interactions has made the study of wind-induced bridge responses a very complicated one. Although much progress has been made in this area in the past few decades, harmful vibrations caused by wind, such as vortex-induced vibrations, still develop under certain circumstances, as has been reported on the Volga River Bridge in Russia and other bridges. More research effort is needed to investigate the effect of the application of new light materials and increasing bridge span lengths and to gain more knowledge of the important parameters that are crucial for wind-resistant design.

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