Ensuring the reliability of bridge structures

Study material for bridge design course

LAB University of Applied Sciences
Bachelor of Civil Engineering
2022
Ilia Shcherbakov

Abstract

Author(s)	Publication type	Published
Shcherbakov Ilia	Thesis	2022
	Number of pages 33	

Title of Publication

Ensuring the reliability of bridge structures

Study material for bridge design course

Degree and field of study

Bachelor of Civil Engineering

Name, title and organisation of the client (if the thesis work is commissioned by another party)

Abstract

This paper investigates the concept of reliability of bridges and ways of its ensuring at the design stage. The described design concept is aimed at preventing the collapse of bridge structures or minimizing their consequences by choosing most reliable design solutions. Since the problem of bridge collapse remains relevant, the distribution, discussion, and analysis of the principles of such approach is necessary.

The main purpose of this paper is to describe the basics of the reliable bridge design approach to civil engineering students. To help students to clearly understand this concept, paper familiarize them with the process of bridge structures evolution and base structural forms of bridges, give a clear explanation of such definitions as reliability and robustness by giving relevant examples of bridge collapse cases, describing the cause of failure, weaknesses of structure, risky solutions, the risks they high and the ways to avoid them. Especially attention is emphasized to the problem of progressive collapse, accidental actions of vehicles, hidden defects, and structures with low robustness.

This paper is based on analyzing of real collapse cases, scientific articles, and opinions of acknowledged civil engineers.

It might be useful as study material for bridge design course for civil engineering students.

Keywords

Reliability, progressive collapse, robustness, bridge, accidental action

Contents

1 Introduction

The Issues of ensuring the reliability of bridge structures despite present high technical level of design, structural materials, and construction process, are still remains relevant. Unfortunately, bridge collapses happen around the world every year and the number of cases tends to rise. It is difficult to underestimate consequences of collapses of bridges. Each such case leads to disruptions in the functioning of the transport network, increase in delivery times and costs. Elimination of consequences of the collapse and restoration of the transport route requires huge amount of funds that are not budgeted. Furthermore, collapses of bridges often lead to human casualties and injuries. Therefore, preventing or minimizing the probability of a bridge collapse seems to be an extremely significant task.

Bridge collapses for a variety of reasons. Around 60% of collapses caused by natural disasters (Platonov 2009), the impact of which cannot be prevented, but another 40% of them caused by design and construction flaws, overload and accidental actions, the influence of which can be avoided or minimized at least to that extent that does not lead to instant collapse. Moreover, sometimes collapses happens when all requirements of design codes are completed and all necessary by rules calculations is done. In other words, these accidents happens because design is mostly based on assumption that service and repair works will be done in time, defects will be found before they lead to failure and moving loads will always move by the right route and have design values. Most of these cases shows that this is not how it actually happens. Another significant feature of bridges is that their main structures are usually hide from ordinary observer, who can notice that something wrong is happening. All the above lead to the conclusion that bridge design requires some kind of special approach.

Therefore, the main objective of this thesis is to describe the basics of the safe bridges design approach to civil engineering students, who are interested in bridge design. In order to help students clearly understand this concept, seems important to familiarize them with the process of bridge structures evolution and base structural forms of bridges, give a clear explanation of such concepts as reliability and robustness by giving relevant examples of bridge collapse cases, describing the cause of failure, weaknesses of structure, risky solutions, the risks they high and, finally, the ways to avoid them.

2 General information about bridge structures

2.1 Historical sketch of the development of bridges

Bridges are among the most advanced structures, which are created by man. The history of the development of bridges and other bridge structures (viaducts, aqueducts, flyovers, overpasses, etc.) shows the history of the development of construction metier in all countries of the world. Initially, the simplest bridge structures were used to transfer people across small obstacles, later, bridges became a necessary part of roads crossing rivers, lakes, ravines, and gorges.

As a material for the construction of bridges, people used natural stone and wood, later with the development of industry–reinforced concrete, metal, and, finally, composite materials. At present time bridges are made of various materials that allows to create different structures, covering spans up to two kilometres (The main span of Akashi Kaikyo Bridge is 1991 m) and providing the movement of vehicles and pedestrians in different conditions of nature and urban area.

2.1.1 The ancient times

In ancient times, to cross rivers and abysses, people used the simplest bridges created by nature, for example a tree overturned by a hurricane from shore to riverbank, as well as the blockage of stones formed as the result of rockfall. The simplest bridges created by nature became a prototype of the first wooden girder and first arched stone bridges created by human using primitive tools. (Salamaxin & Popov 2017, 4.)

At the same time, plexus of tree branches hanging over rivers, prompted the people of the ancient India to create “live” suspension bridges weaving roots of rubber plant (Image 1).

Image 1. “live” suspension bridge in India (Image: Rohit Mordani)

One of the first types of bridges used in ancient times to cross wide water barriers were floating bridges based on the well-known simple idea of buoyancy of various materials and objects. They widely used in military campaigns to overcome a water barriers encountered on the route of the troops, since they do not require difficult for that time work of building rigid supports. It is known that the troops of Alexander the Great carried with them pontoon bridges in the form of leather bags inflated with air and wooden boats disassembled into parts. (Salamaxin & Popov 2017, 5.)

From the documents of ancient history, other information about bridges in ancient Greece, Rome and China is also known.

There is information about the timber bridge built by the Romans across the Tiber River in 638-614. BC (Salamahin & Popov 2017, 6). It is important to mention this bridge, because the structure of it (Figure 1) was already same as modern simplest wooden girder bridges.

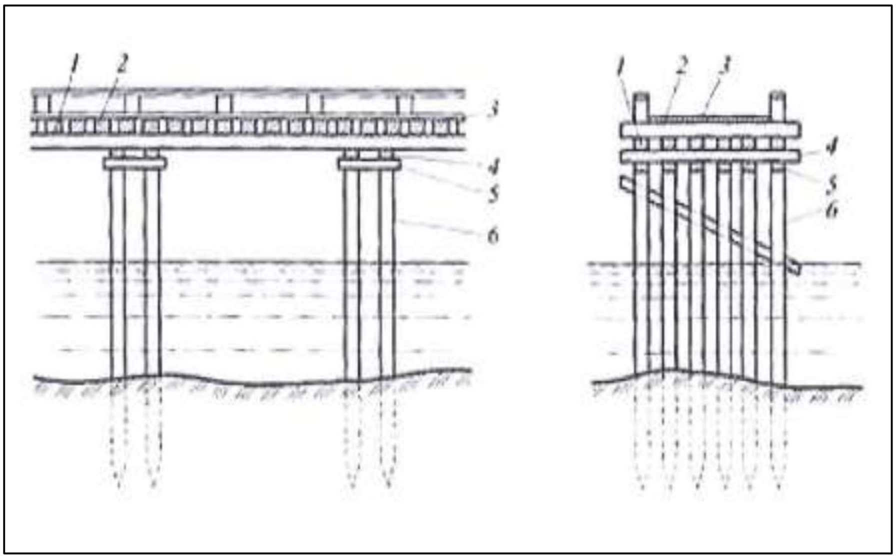

Figure 1. Structure of bridge across Tiber River built by Romans. 1 – girders, 2 – secondary girders, 3 – deck, 4 – pier cap, 5 – bracing, 6 – pile (Salamahin & Popov 2017, 6)

A bit later the Romans invented pozzolanic cement, which allowed them to start mass construction of stone bridges. That bridges had a circular arch form, which provided compression in all sections of span. At that time, this was the only possible structure, because the mortar between the stones cannot work on tension.

One of the surviving Roman bridges is the Alcantara Bridge in modern Spain. This bridge was built in 104-106 CE and have an arches, each spanning 29 metres (Image 2) (Billington).

Image 2. Alcantara Bridge (Image: Salta Conmigo)

At the same time the first bridge over the Danube River was built by the ancient Greek builder Apollodorus of Damascus during Trajan campaign against the Dacians in 104. It had 20 stone supports with high of 46 m and about 18 m wide. Spans were 35 m long and were covered with wooden arches made up of three rows of beams (Image 3). The remains of the pillars of this bridge have survived to our time. (Kalmikov 1957, 18.)

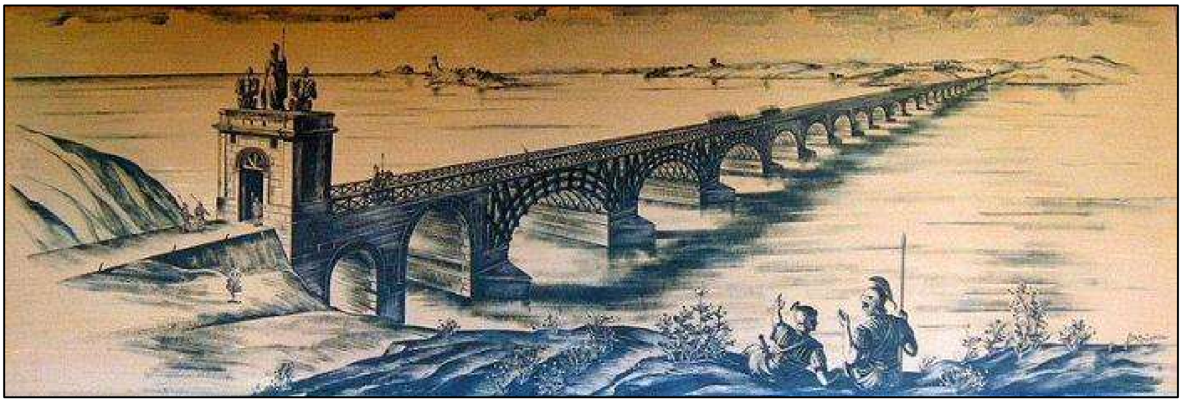

Image 3. Bridge of Apollodorus over the Danube (Image: U. Rapsak)

The Bridge of Apollodorus with wooden arch spans illustrate a big step in developing of bridge structures, by gathering best solutions of previous structures. Girder wooden bridges can cover spans only up to 14-16 meters, so to build a girder bridge over the Danube, at least twice more supports required and reached the number of 40. In addition, wooden supports in the zone of variable water level do not last long. A stone bridge with similar spans would be too high because of circular-arched form, heavy and difficult to build. So, antique engineer decided to use stone only in supports, replacing it from arched spans by a material capable to work for bending, and got fundamentally new structure. This case demonstrate the process how structures were evolving from ancient times to the present day.

2.1.2 The Middle Ages and Renaissance

The era of stone and wooden bridges continued after the fall of the Roman Empire for many centuries. In the construction of bridges, nothing significantly changed until the 19th century. However, they had some peculiarities. It is worth noting, that the shape of arches in that time were modified to ogival, or pointed arch, which reduced the risk of sagging at the crown of an arch and decrease horizontal force at the abutments. (Billington.) One of these bridges is Pont del Diable in Spain, which was built in 1283 year (Image 4). The main span of bridge is 37.3 m.

Image 4. Pont del Diable (Image: Sansar)

Another feature of medieval bridges was that towers, houses or shops were often built on them. The most illustrative bridge of that was Old London Bridge, completed in 1209 (Image 5).

Image 5. Old London Bridge (Encyclopedia Britannica)

During the Renaissance the Italian architect Andrea Palladio used the principle of the roof truss and designed several successful wooden bridges with spans up to 30 metres. Longer bridges, however, were still made of stone, but by that time new rational shape of arches was designed by Bartolommeo Ammannati and used in his St Trinity Bridge (Image 6). This elliptical shape of arch, in which the rise-to-span ratio was as low as 1:7, became known as basket-handled and has been adopted widely since. (Billington.) Thus, the ability to build flatter arches made it possible to eliminate the dependence of the height of the bridge on the required span, which made them less material-intensive and give more ability to fit into the urban landscape.

Image 6. St Trinity Bridge (image: Erik Parker)

Later, Jean-Rodolphe Perronet, developed very flat arche bridges, for example Pont de la Concorde (Image 7), which became a pinnacle of stone bridge building (Billington).

Image 7. Pont de la Concorde (Encyclopedia Britannica)

It is worth noting the achievements of wooden bridge building at the end of this period, which reached new span lengths up to 108 meters due to the widespread use of different types of timber trusses. The most used were the lattice truss of Town, and later the trusses of Gau with spans up to 60 meters. Initially, the reliability of such trusses left much to be desired, since there was no theory of calculation justification, but this changed with the development of theory of calculating multiple trusses by Zhuravsky (Salamaxin & Popov 2017, 12-13), which is an example of one of the ways of raising the reliability of bridges.

2.1.3 Industrial revolution - nowadays

The turning point for bridge building was the industrial revolution, which made metal an affordable building material. At first it was cast iron. It can be said that cast iron made it possible to combine the advantages of stone and wooden structures, taking strength from the first and delicacy from the second. As a result, the dead load on the structure was significantly reduced. The first bridge made of cast iron was built in 1779 by Abraham Darby in England and have a 30 meters span (Image 8) (Johnson). Since cast iron has low tensile strength, the bridge was made arched, like a stone one and the joints between elements were made same as they were made in timber structures (Image 9, right part), which again, illustrates the mentioned principle of the evolution of bridge structures and their succession.

Image 8. Ironbridge (Johnson)

Another important step in the development of bridge construction was the invention of Portland cement in 1824, which in several properties turned out to be significantly better than previous types of cements. But this did not change the main thing - concrete still poorly resisted tensile stresses.

Since both concrete and cast iron have low tensile strength, a real revolution in bridge construction occurred with the advent of structural steel, which had the same high compressive and tensile strength. Previously, bendable structures could only be made of wood, the strength of which was not high, and the sections of the elements were limited by the natural dimensions of the tree trunk. In addition, the transmission of tensile forces in wooden structures was difficult to ensure. Now those restrictions became a thing of the past. Moreover, steel made it possible to make bendable elements from concrete, by reinforcing it. All of this made bridge structures so various, that it makes sense to conduct further consideration of them according to their structural forms.

2.2 Structural forms of bridges

Generally, according to structural forms of superstructure, bridges can be divided for simple-supported spans, continuous spans, cantilever spans, rigid frames, arches, cable-stayed bridges, suspension bridges and combined systems.

2.2.1 Simple-supported bridges

This type of bridges consists of beams or slabs simply supported at both ends. Each span is statically determined structure in this case, which makes them resistant to uneven settlements of supports. The maximum bending moment is always in the mid of span and maximum value of shear force at supports. This made them easy to calculate, design and manufacturing. Most of these bridges nowadays are made of precast concrete beams, installing by jib cranes (figure 2), but they can also be made of steal or cast in situ concrete. However, simple-supported bridges have the least overlapping ability comparing with other types of bridges and are used for spans up to 33 meters (in Russia), which is maximum length to be transported by auto-road.

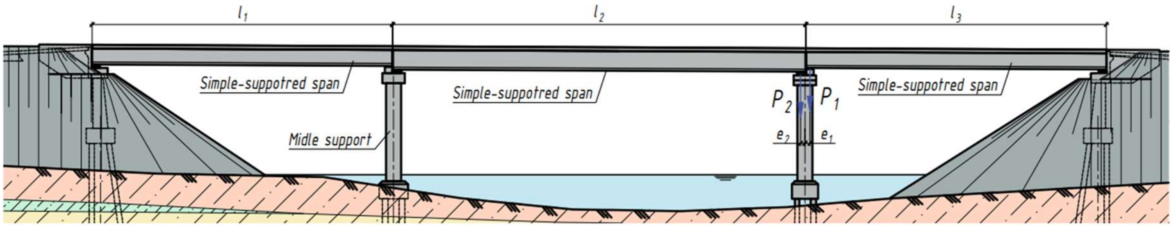

Figure 2. Simple-supported bridge

Previously, one of disadvantage of such bridges was a number of expansion joints, which were made behind every support, but nowadays adjacent spans are usually combined into temperature-continuous lash.

2.2.2 Continuous bridges

A superstructure of continuous bridges is statically indeterminate, which make them fundamentally different comparing with simple-supported. They are more difficult in calculation, design, and manufacturing, they receive additional forces from the uneven settlements of supports, but they have much bigger overlapping ability comparing with simple-supported – up to 200 m or even more, because of unloading effect of adjacent spans. It can be easily seen from influence-line of banding moment in the middle section of central span (figure 3). Bending moment in any section can be calculated as multiplication of distributed load and an area of influence-line behind this load. Blue parts of the influence-line, corresponding to the position of the loads on the external spans, have a negative value, which means that any positive load on external spans, mainly their self-weight, create a negative moment in the mid of central span, when the moment from any positive load on this span is positive. In total, the moment is much less then in same simple-supported span. This phenomenon is a reason why spans of continuous bridge can be much longer then simple-supported span with same cross section.

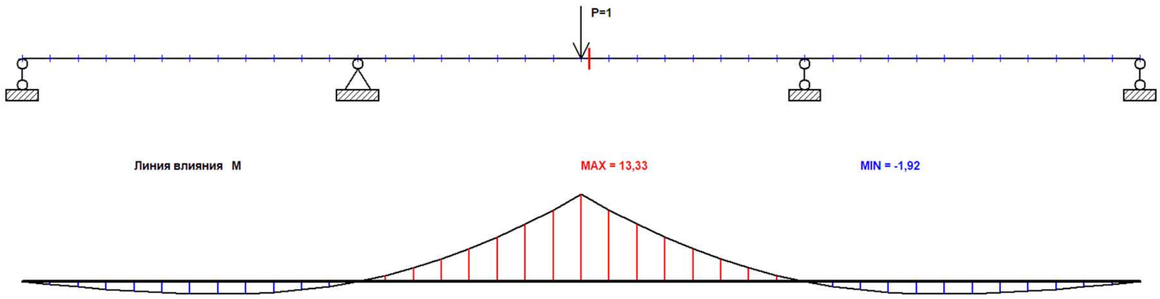

Figure 3. The influence line of bending moment in the mid of continuous span

But interdependency of spans, presence of negative and fluctuating moments around middle supports (figure 4) makes their design more complicated.

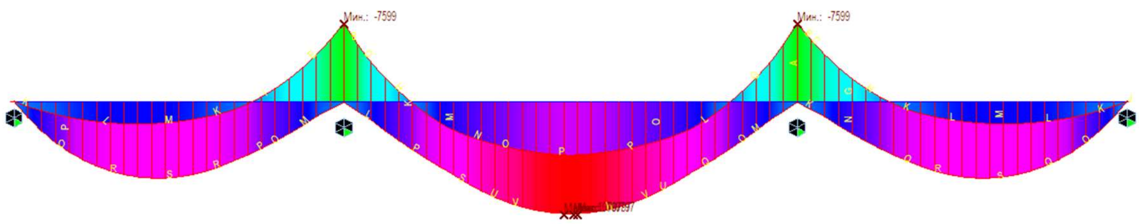

Figure 4. An example of bending moment diagram for continuous beam.

Another advantage of continues bridges is that they need only one row of bearings, which can be placed at the center of support (figure 5) and transmit the reactions without eccentricity, comparing with simple-supported beams, which requires two rows of supports (Image 10).

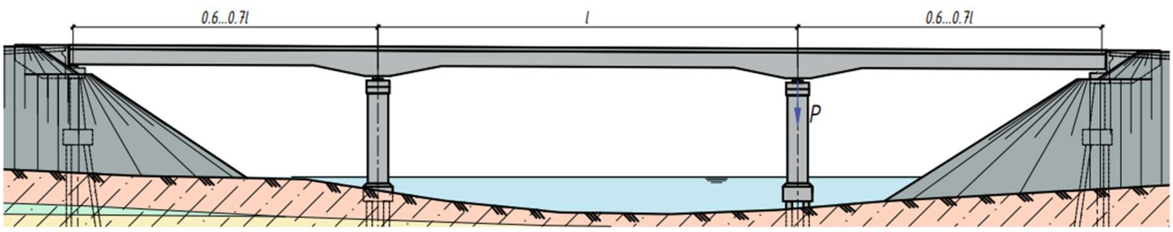

Figure 5. Continues bridge

2.2.3 Cantilever bridges

The cantilever bridge is bridge, whose superstructures have overhanging parts. The superstructure of cantilever bridges consists of an anchor arm located between the supports and a part hanging from the support (cantilever arm). The distance between two consoles is covered by suspended span (figure 6).

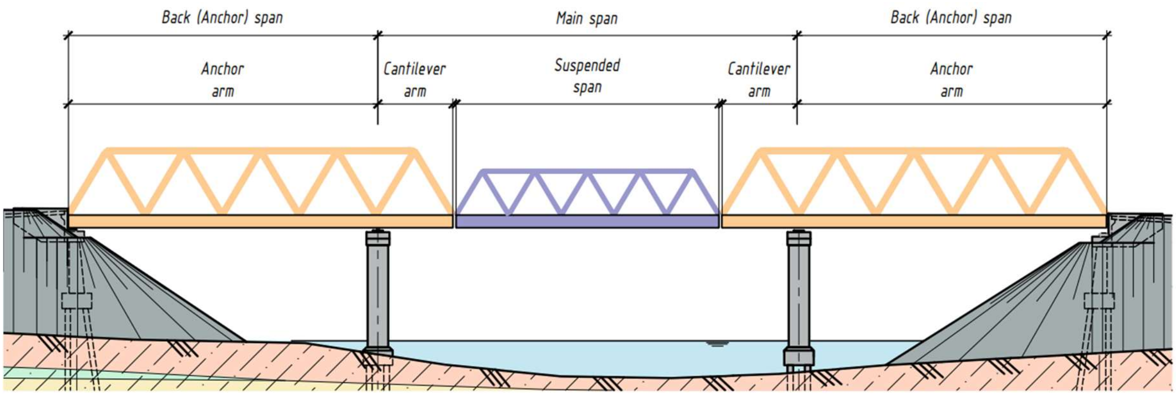

Figure 6. Principal structural scheme of cantilever bridge

Spans of cantilever bridges are statically determined structures, same as simple-supported beams, so they have same advantages: resistant to uneven settlements of supports and absence of fluctuating forces, but they have bigger overlapping ability, because their most loaded section is located behind middle supports – the place, where any size of section can be made without causing any extra bending moment from the self-weight of this part of structure.

The cantilever bridges have few disadvantages. First is that internal hinges between spans cause a longitudinal profile fracture (figure 7), which increase dynamic actions on structure and decrease the smoothness of movement. In addition, the cantilever spans need to have high stiffness, to minimize the deflection, so that is way they are usually made into trusses, which limits their architectural diversity.

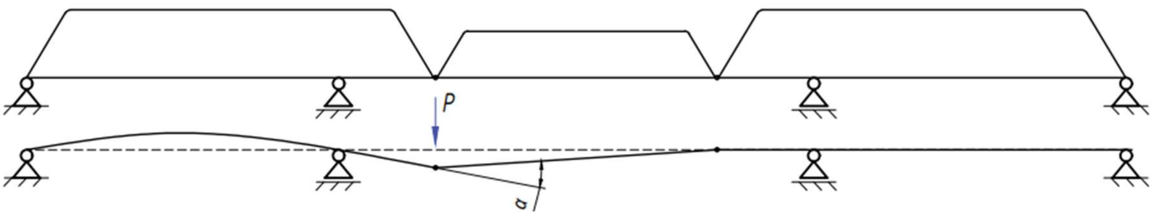

Figure 7. The deflection line of cantilever bridge

Another disadvantage of this type is that their stability depends on the stability of the anchor span. This means that the failure of the anchor span will lead to the progressive collapse of the entire structure.

2.2.4 Rigid-frame bridges

In rigid-frame bridges deck is rigidly connected to the piers, that is why they are usually made of concrete, since it is difficult to make enough rigid joint with metal. These bridges are very diverse according to their structural scheme. They can have or not have internal bearings into superstructure. In the first case they are usually statically determined structures, in the second – indetermined.

Figure 8 shows a bridge, consist of several T-frames, which are statically determined structures with related advantages. Moreover, the transom of this frame works only for negative moment, which greatly facilitates the use of prestressed concrete and the balanced concreting technology (image 17) almost indispensable for high bridges. These bridges can also have suspended spans (figure 8).

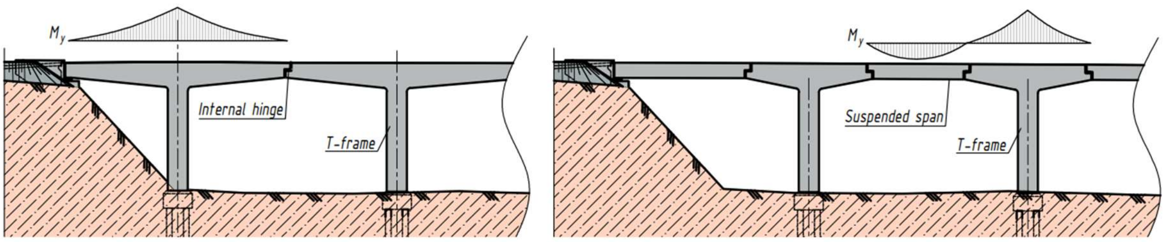

Figure 8. Rigid-frame bridge with T-frames

Image 9. Balanced concreting technology (PERI)

Another type of statically determined frames is shown in the figure 9. In this case bending moment in the middle of span is less than in simple-supported beam with the same span, which allows to make span thinner, especially when it is required to ensuring the bridge clearance.

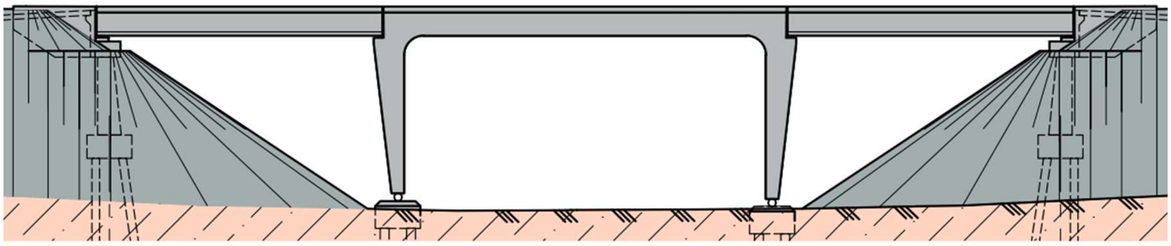

Figure 9. Inverted-U-shaped rigid frame-bridge

Figure 10 shows a rigid-frame bridge without internal hinges. This solution leads to appearance of bending moment in the middle of span, opposite to the first case, but the value is less than in continuous bridges. But because of high index of static indetermination such bridges can be built only on reliable soils and have no more than 3 spans to avoid high extra forces from thermal expansion.

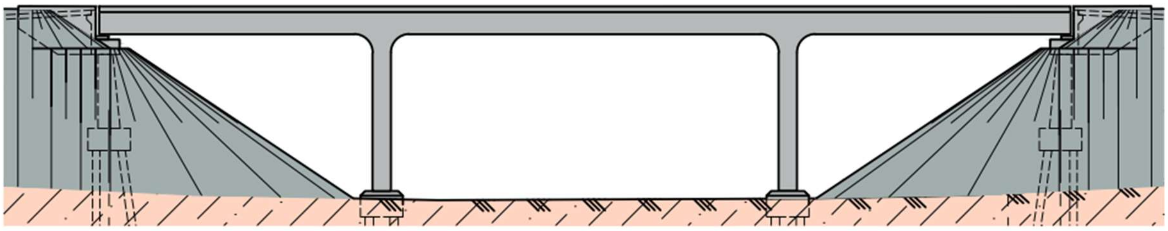

Figure 10. Continuous rigid-frame bridge

Frame bridges can also have slant lags, which made them quite similar to an arch bridges. In this case the presence of an arch trust (horizontal component of support reaction) leads to decreasing the bending moment in the middle of span. But consequently, this requires a hard soil to extend this force.

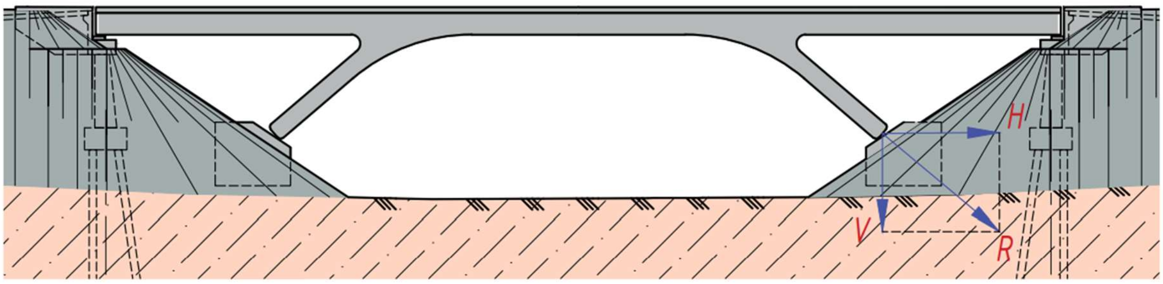

Figure 11. Rigid frame-bridge with inclined (slant) legs

2.2.5 Arch bridges

Modern arch bridges significantly different from their ancient and medieval predecessors. Nowadays arche bridges mostly are made of steel or concrete. They vary by the deck location for deck arch, through arch, and half-through arch as shown in the figure 12. The choice of type depends on local terrain conditions.

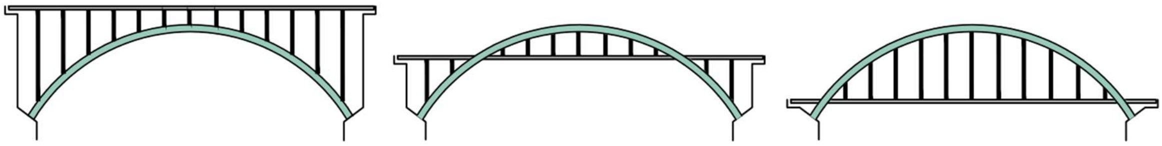

Figure 12. Types of arch bridges, according to deck location

Arche bridges are also differed in the number of hinges: hingeless arch, single hinged, two-hinged or three-hinged (figure 13). The first is statically indeterminate, the second is statically determinate with their inherent advantages and disadvantages. The last one is frequently used in bridges because of insufficient stiffness.

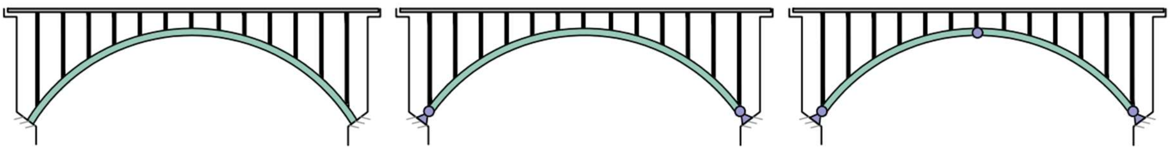

Figure 13. Types of arch bridges, according to number of hinges.

Arch bridges shown in figure 12 and 13 transfer horizontal thrust to their supports (figure 14A), which required suitable ground conditions to use these systems. However, there are arch bridges without external horizontal thrust, which in these systems is taken by the tie-beam connecting the ends of arch (figure 14B). But practically, the effect of decreasing a bending moment by arche thrust is less in this case.

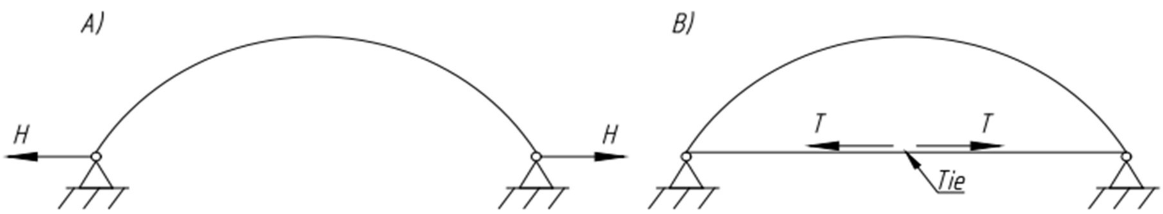

Figure 14. Arches with and without external horizontal thrust.

2.2.6 Cable-stayed and suspension bridges

Thess types of bridges has the biggest overlapping ability and are indispensable in conditions, where the construction of intermediate supports is difficult, irrational or impossible, for at great depths. Now the longest span for cable-stayed bridges is 1104 m (The Russky Bridge), and for suspension bridges is 1991 m (Akashi Kaikyo Bridge). Another significant advantages of suspension and cable-stayed bridges, except their overlapping ability, are construction technology of superstructure, which do not require any false work, as cable erection method is used, and their aesthetic appearance. (Weiwei, L. & Teruhiko Y.)

A cable-stayed bridge is a system, which consist of bridge deck suspended by inclined stayed cables, fixed on pylons (Figure 15).

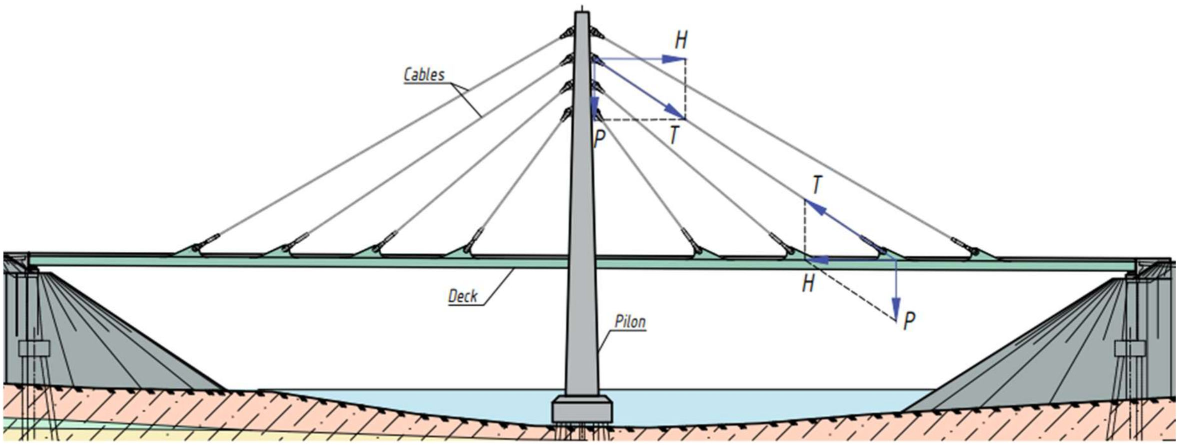

Figure 15. Cable-stayed bridge

The large overlapping capacity of these types of bridges is explained by the fact that their main elements mainly work either in compression or in tension, which allows to use their cross-sections and material properties with maximum efficiency. In case of cable-stayed bridges, vertical forces applied to the deck is converted into tensile force in cables, which causes compression in deck and orthogonal components, applied to pilon. Since cable-stayed bridges are usually symmetrical, the horizontal components from constant loads are balanced, so the pylon mostly works in compression and slightly in bending only from asymmetrical moving loads.

Suspension bridges has similar working principle, but the main load carrying members of this system are main cables, to which the deck is hung by usually vertical suspenders. The tensile force from the main cables can be transferred outside the system to anchorages or can be taken by the deck – same as in arch bridges, but with opposite direction. In the first case suspension bridge is externally anchored, in the second – self-anchored (Figure 16).

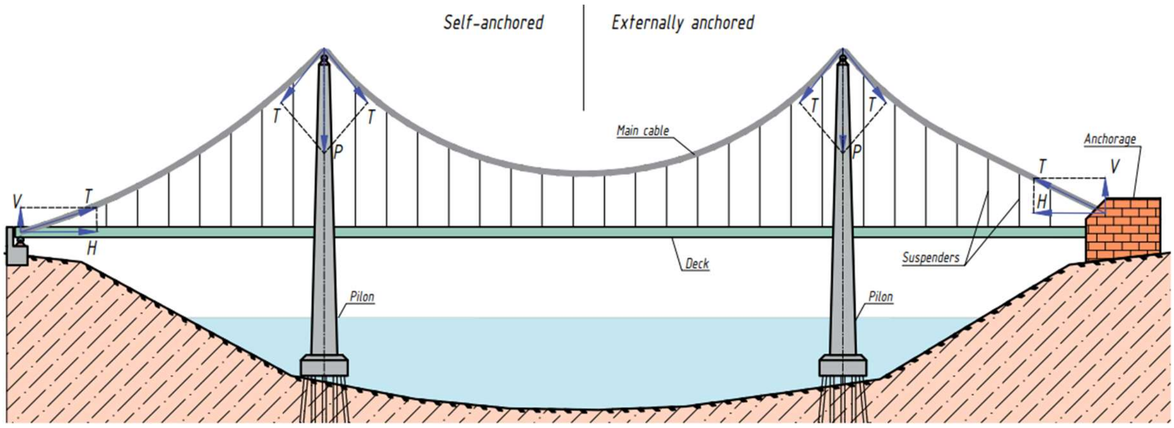

Figure 16. Suspension bridge

3 Reliability of bridge structures

3.1 Current state of the problem

Despite present high technical level of design, structural materials and construction process, bridge collapses happen around the world every year and the number of cases tends to rise, according to the statistic, shown in figure 17.

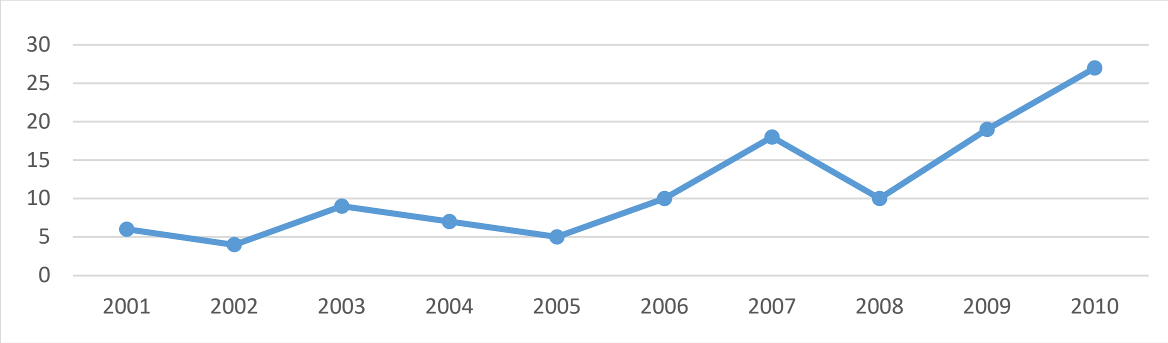

Figure 17. Collapse cases of bridges around the world in the period from 2001 to 2010 (adapted from Eremin et al. 2011, 307)

It is difficult to underestimate consequences of collapses of bridges. Each such case leads to disruptions in the functioning of the transport network, increase in delivery times and costs. Elimination of consequences of the collapse and restoration of the transport route requires huge amount of funds that are not budgeted. Furthermore, collapses of bridges often lead to human casualties and injuries. Therefore, preventing or minimizing the probability of a bridge collapse seems to be an extremely significant task.

The probability of failure is described by the term reliability. Reliability is ability of a structure or a structural member to fulfil the specified requirements (SFS-EN 1990, 14).

Bridge collapses happen for a variety of reasons, divided into internal causes and external causes. Internal causes include design error, construction mistake, lack of maintenance, material defect, etc. External causes include natural impacts such as earthquake, flood, fire, and wind, as well as extreme loads such as collision and overload (Guojing et al. 2022). The design of structures is carried out considering the possibility of the impact of such external factors with a certain magnitude, which is determined by surveys as the maximum possible value of the impact, defined with specified exceedance probability, which is set by design codes. Thus, operability limits of structure under impact of certain factor, are determined depending on the acceptable value of risk of failure. So, if the failure occurs under the influence of external factor exceeding the design value, then the structure cannot be considered insufficiently reliable. However, failures often caused by a combination of external and internal factors, and in this case magnitude of damaging impact is usually less than design value. Therefore, increasing the reliability of structures, by reducing the exceedance probability and increasing the safety factors, when they are economically justified, does not seem reasonable and effective. Another question is whether the impact could have been prevented. On the other hand, it is also impossible to increase reliability by excepting influence of internal factors, since the requirements for their prevention are already presented at an extremely high level, which still does not guarantee their complete absence. Thus, hereinafter, the increase in reliability means measures not related to the revision of the principles of calculation and quality control, but measures related to

- prevention or reduction of the probability of accidental actions
- timely detection of critical defects
- prevention of progressive collapse
- increase in robustness

Each of those bullet points will be considered in more detail below.

3.2 Bridge reliability factors

3.2.1 Accidental actions

Accidental action is an action, usually of short duration but of significant magnitude, that is unlikely to occur on a given structure during the design working life (SFS-EN 1990, 16). Among the accidental actions described in EN 1991-1-7, the most significant for bridges are impacts caused by road vehicles, derailed rail traffic and ship traffic. These impacts are usually caused by the exit of the vehicle or its parts outside the clearance of the structure.

There are two main types of impacts from road vehicles EN 1991-1-7 distinguishes: impacts on supporting substructures and impact on superstructure, which is rightly confirmed by the number of accidents.

There are many cases of bridge collapse due to the collision of dump trucks with a raised body: the overpass near Orenburg (Karavanskiy 2015), the pedestrian bridge on the road M-10 (Image 10) (Interfax 2016), the pedestrian bridge on the road P-242 (Dorinfo 2022), the overpass in Pavlodar region, Kazakhstan (Tengrinews 2019), the pedestrian bridge in Helsinki (Yle 2010), the overpass above Georgia's I-16, USA (@GDOT East Traffic 2021) and others.

Image 10. Pedestrian bridge collapse on the road M-10 (Interfax 2016)

Since in such cases, the driver of a dump truck or truck crane does not know about the raised body or boom, despite the presence of warning systems in modern machines, to prevent such incidents an installation of laser clearance gates is looks like a good solution. At present, such systems are not widely used; at the moment, two cases of application have been found: in Ottawa city, Canada (Telegram 2014) and near Tumen city, Russia (Ural-meridian 2020) (Image 11).

Image 11. laser clearance gate system

Another common type of accidental actions caused by road vehicles and ships is collision with pillars. The examples are overpass collapse in Ekaterenburg, Russia (Interfax 2011), the collapse of pedestrian bridge in Krasnoyarsk, Russia (Dela.ru 2014) (Image 12) and the largest accident of this type - I-40 bridge disaster in 2002, Oklahoma, United States (E

Eremin 2011, 32). The collapse of three spans of the bridge occurred as a result of a collision of a barge with a support (Image 13).

Image 12. the collapse of pedestrian bridge in Krasnoyarsk, Russia (Dela.ru 2014)

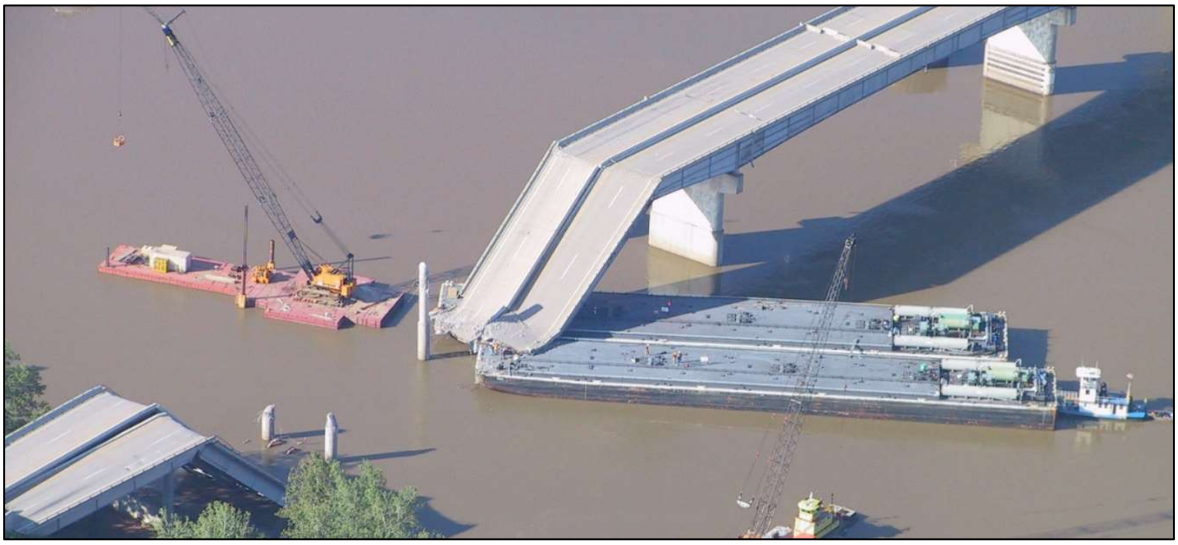

Image 13. I-40 bridge collapse (Protectnepa)

It can be seen in image 13, that the pillars of the destroyed support had a very small thickness and definitely were not designed to withstand such accidental loads, because the navigable route was located under the next span, which had more massive supports. This case demonstrates that it is important to take into account in bridge design the likelihood of vessels drifting off course not only in the limits of navigation span, but also over the entire width of the water area.

Thus, generalizing the collisions of road vehicles and ships, thin pillars of supports in navigable waters and close proximity to the roadway should be avoided.

3.2.2 Critical defects

A significant part of bridge collapses occurs due to untimely detection and elimination of critical structural defects. One of the recent and most famous cases is the collapse of Morandi bridge in Italy on 14 August 2018 (Image 14).

Image 14. Collapsed Morandi Bridge (Image: Nadia Shira Cohen)

What exactly caused the collapse is still unknown, but experts found an evidence of corrosion of stay cables. In the case of Morandi Bridge the cables were difficult to inspect, since they were covered with concrete. (Mattioli 2019).

Although prestressed concrete stays are not currently used in new bridges, this case shows that all load-baring elements of structure must be available for inspection and repair. However, there are some solutions common in modern practice contradicts this requirement. For example, such solution is leave-in-place form (Image 15), that is widely used in composite-girder bridges.

Image 15. leave-in-place form (Image: Inventure Holdings)

Leave-in-place form greatly simplifies slab concreting, but in case of waterproofing damage, it, firstly, contributes to the accumulation of water in concrete, and secondly, hides the fact and place of leakage, that leads to extensive corrosion of reinforcement and shear connectors (Syrkov 2021) (Figure 18). Shear connectors are small but very important elements of composite-girder bridges since they provide connection between concrete slab and steel beam to make them work as parts of one section, that is way corrosion of this elements leads to significant reduction in bearing capacity of superstructure.

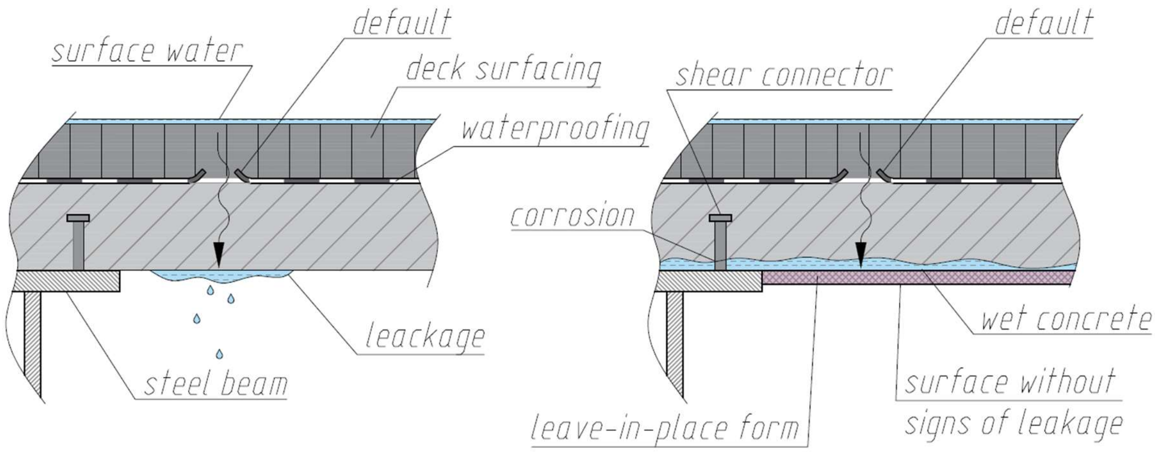

Figure 18. Details of structure with and without leave-in-place form

Another relevant example of failure due to the degradation of the hidden main load-bearing elements is collapse of Troja footbridge in Prague in 2017 (Image 16).

Image 16. Troja footbridge in Prague (Image: StrawberryLab)

The fact that the condition of the bridge was a cause for concern was known long before the tragedy, that is why the bridge was electronically monitored in real time since 2013, but it did not help to prevent the collapse (Lazarova 2017). In stress ribbon bridge the main load bearing elements are prestressed steel cables, usually located into or under deck slab. The most probable cause of the collapse is the corrosion of these cables, which were not available for inspection since they were placed into concrete deck (Image 17).

Image 17. The deck of Troja footbridge after collapse (Image: Vit Simanek)

In fairness, it should be noted that for prestressed concrete structures the internal location of tendons is normal and rarely causes problems in case of proper provision of crack resistance. But the thin section deck of stress ribbon bridge has quite small stiffness, that make them not resistant against cracks enough. The presence of cracks reaching the reinforcement guarantees corrosion, since it provides contact of steel with atmospheric air. It seems that in the case of Troja footbridge, cracks appeared in the deck and led to corrosion, which was accelerated by use of anti-icing agents mentioned by professor Strasky in the process of litigation (Mizzy 2022). It should be noted that the corrosion of prestressed reinforcement is especially dangerous, since when the tensioned wire cross section is reduced to a critical size, it breaks sharply, but not slow fluidity, as in the case with non-prestressed reinforcement. This fact raises doubts about the correct choice of the monitoring system, the function of which was to measure structure deflection. The inability of such system to detect signs of an impending collapse is confirmed by the fact that immediately before the collapse, the magnitude of the deflection was normal (Lazarova 2017).

Image 18. The Troja footbridge after collapse

The district court stated that the project of Troja footbridge was flawless (Mizzy 2022) and there are no objective grounds to say that this is not so, because probably with proper maintenance and operation the collapse would not have happened, but seems that main design solution cannot be said to be reliable, because it did not allow assessing the condition of the tendons and led to instant collapse caused by undesirable but possible deviation from service conditions.

3.2.3 Progressive collapse

Unlike exposure to influence of accidental actions and critical defects progressive collapse characterizes not the cause but the consequences of failure. Progressive collapse is a chain reaction of failures that caused by the local destruction of a relatively small part of the structure, resulting eventually, in the collapse of an entire structure or a disproportionately large part of it (ASCE 7, 2005; Ovchinnikov et al. 2020, 17). Eurocode does not define this term directly but contain a requirement that structure shall be designed and executed in such a way that it will not be damaged by events such as explosions, impact, or the consequences of human errors, to an extent disproportionate to the original cause (SFS-EN 1990, 23). Thus, the need for protection against progressive collapse is explained by the necessity to reduce the consequences of local failure, which could not be avoided.

An exemplary case of a progressive collapse is collapse of Jiujiang Bridge in 2007 in China. The collapse caused by collision of barge with a pier. As a result, four spans of continuous girder superstructure and three intermediate piers collapsed (Figure 19, 20).

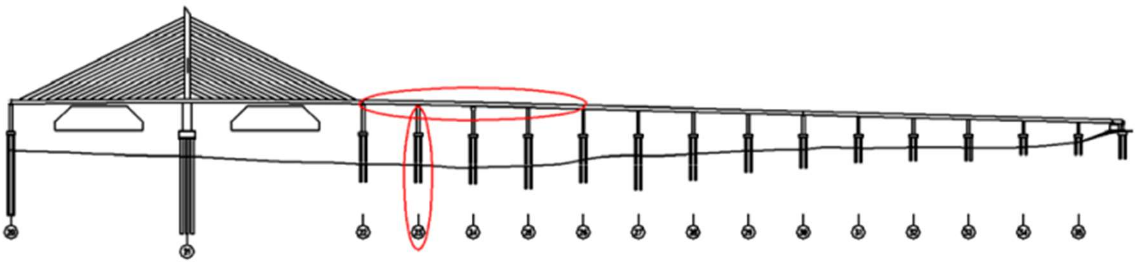

Figure 19. Span arrangement of the Jiujiang bridge (Zhao et al. 2014)

The investigation showed the impact of barge exceeded the design value of such accidental force, that led to failure of this support, which caused extra forces in superstructure and other supports exceeding their load-bearing capacity.

A progressive collapse of this type is difficult to prevent because the causes are inherent in the continuous superstructure itself, since, firstly, the support section of girder with negative bending moment becomes a middle section with positive bending moment, and secondly, because of redistribution of efforts in adjacent spans.

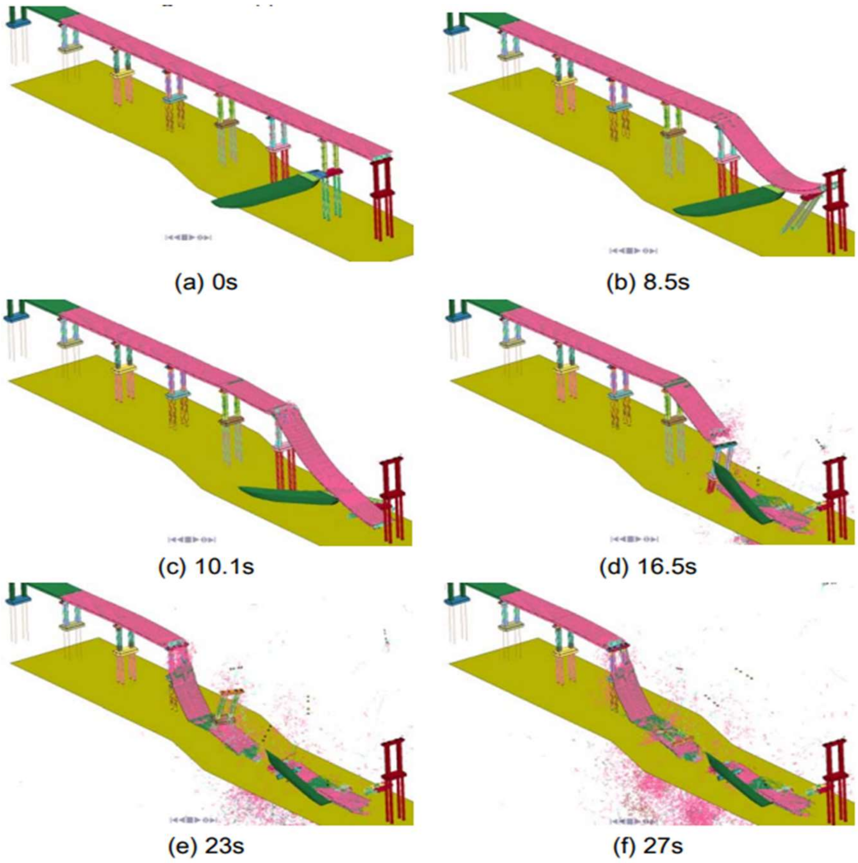

Figure 20. Collapse process of the Jiujiang bridge (Zhao et al. 2014)

However, if the destruction occurs in the superstructure, then the progressive collapse can be prevented. For example, in 1986 a 63-meter span of continuous prestressed concrete bridge over Suhona river in USSR collapsed due to corrosion of tendons (Syrkov 2021) (Image 19), but despite the elimination of the unloading effect of adjacent span and redistribution of efforts, collapse did not spread to other spans. Later the collapsed span was replaced by metal simple-supported girder. (Image 20)

Image 19. The collapse of the bridge over Suhona river (Syrkov 2021)

Image 20. The bridge over Suhona after repair (Syrkov 2021)

However, not only statically indeterminate systems are subject to progressive collapse, but also statically determinate, especially cantilever systems, as shown in figure 21 and image 21.

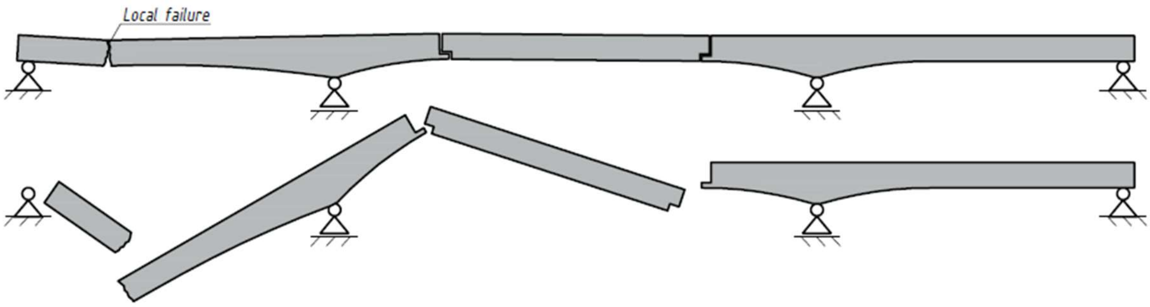

Figure 21. A possible variant of collapse of cantilever bridge

Image 21. Collapsed Palmburger bridge in Kaliningrad (Image: Rybakov Andrey)

A similar incident could have happened in Rostov-on-Don in 2007 due to rupture of 28 tendons of anchor span, but the defect was detected during the inspection and temporary support was installed to prevent a collapse (Image 20). It is also worth noting that the collapse did not happen since the span consisted of two parallel beams, and undamaged one took an extra load on itself (Syrkov 2021). Such mechanism of behavior of structure in case of local failure rather reflects the robustness, which will be discussed in next subsection.

Image 20. Old Voroshilovskiy bridge in Rostov-on-Don (adapted from T.K.M.)

For cable-stayed bridges, the problem of progressive collapse is also relevant since the elements of such systems are highly dependent on each other. Experts notes some dangers of such structures associated with progressive collapse. Wolf and Starossek (2007, 17) points out the vulnerability of the cables to damage by vehicle impact or vandalism and says that the loss of a cable must be considered as a possible local failure, that might lead to the overloading and rupture of adjacent cables or increase of buckling length of stiffening girder, which is under high compression, especially near pylons. Thus, to prevent a progressive collapse, cable-stayed bridges should be analyzed for a case of lost of cable.

Summing up the above, countering the progressive collapse might be built on the following five statements, formulated by Professor Perelmuter A. (Ovchinnikov et al. 2020, 14):

- The possibility of occurrence of local failures of the structural system should be taken into account. Complete protection against them is fundamentally impossible. Therefore, the task of the designer is to understand the origin of such destruction, assess the likelihood of their implementation in relation to the structural elements, and assess the possible consequences.
- The most dangerous of the possible consequences is the chain development of destruction (the domino effect). Consequence: the task of the designer does not include the analysis of the entire possible chain of progressive destruction, it is only necessary to evaluate the very possibility or impossibility of continuing the process of local damage (the principle of control of the first step).
- If an action, which lead to local failure, can be prevented or the impact can be significantly reduced, then measures for it should be taken.

- Modeling of a local failure by removing an element from the model gives insufficiently accurate results, therefore, modeling should be carried out taking into account the dynamics of the process.
- If the chain development of the process is inevitable, then the main task is to localize and manage the consequences.

3.2.4 Robustness

Robustness, in relation to building structures, can be defined as the ability of system to retain reliability after local failure. This concept is best illustrated by the collapse of suspension Silver Bridge (Image 21) in 1967 in USA. The main load-bearing elements of suspension bridges at that time were steel chains, but not cables like it is now.

Image 21. Silver Bridge, USA (West Virginia & Regional History center)

These chains consisted of eye-bars connected by pins as shown in image 22.

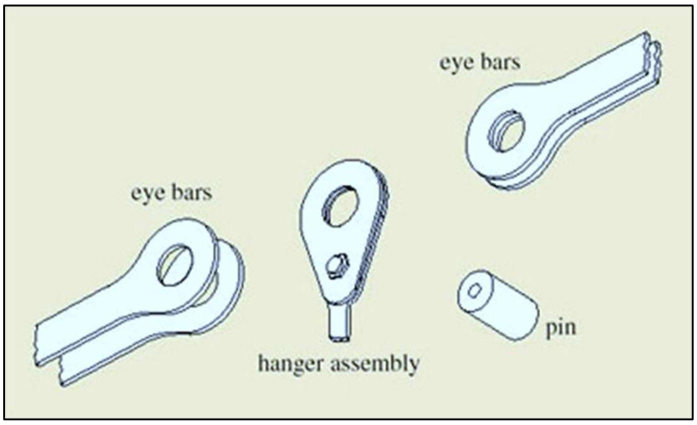

Figure 22. Structure of critical eye-bar joint (The Open University)

Investigation concluded that the collapse initially caused by a small stress crack, around three millimeters deep, inside the bearing loop of eyebar 330. The crack had grown around an impurity in the steel and had been aggravated by the elements and the natural movements of the eyebar along the pin over the 39 years of the bridge's use. (Reimann, 2017). Thus, after the destruction of the eye-bar joint, the load-bearing chain instantly lost its bearing capacity and the bridge collapsed.

Even though this solution is no longer used in modern bridge structures, it clearly shows the essence of critical nodes and elements. In this context, a critical node (or element) is understood as a node, on the integrity of which the stability of the entire structure depends. In other words, the failure of one such node leads to the collapse of the entire structure. From the above example, it follows that the more critical nodes are in the structure, the less reliable it is, especially if they are highly stressed. As noted above, reliability is a probabilistic concept, so, simplifying, if the probability of failure of one node is small, but exists, then the probability of failure of one node out of ten is ten times higher.

Returning to the case of collapse of Morandi bridge, it can also be noted that these structure type had no robustness, since the stability of each of 200 m long section of the bridge just depended on the integrity of any one out of four cable stays (figure 23), which were difficult to inspect and repair.

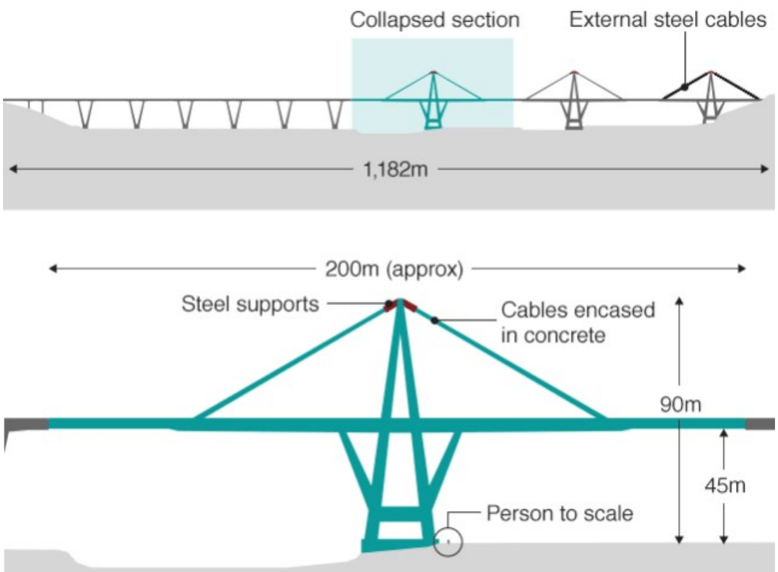

Figure 23. A diagram of the Morandi bridge. (Superior Council of Scientific Investigations)

Thus, a logical and more reliable approach in the design of bridge structures is to "deconcentrate the bearing capacity" by replacing one bearing element of a large section with several elements of a smaller section. This principle can be seen comparing the Morandi bridge with modern cable-stayed bridges, which have a lot more cable stays.

One of the examples confirming this statement is above-mentioned Old Voroshilovskiy bridge. The superstructure of bridge consists of two prestressed concrete box-girders, rigidly connected to each other by concrete deck (figure 24). With great certainty it can be said that this solution saved the bridge from the collapse when 28 tendons of anchor span ruptured, because if same proportionally happened with one-box girder superstructure it would more likely collapsed.

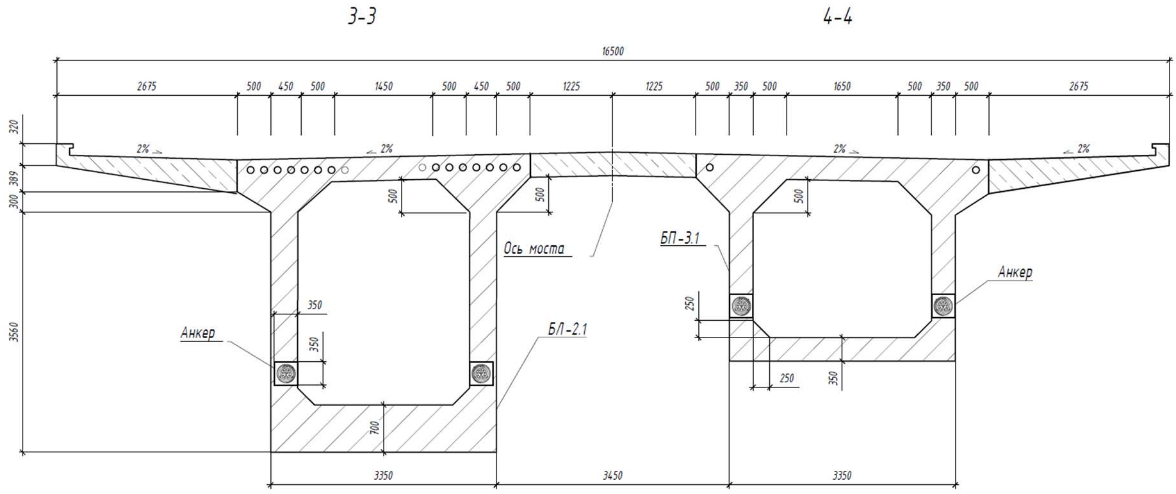

Figure 24. The cross-section of Old Voroshilovskiy bridge

However, when using this principle, it is necessary to design such structural elements, which are subjected to additional loads in cease of local failure, with some margin of bearing capacity and providing redundant load transfer paths.

4 Summary

Bridge structures have always been and remain the most important elements of the transport infrastructure, but at the same time they are the most vulnerable and expensive parts of it. The high cost of the structure itself, as well as the cost of its collapse, requires high attention to ensure the reliability of it. Bridge structures have changed over the centuries, becoming more rational and long-span, but not every new design solutions were reliable enough. There are hundreds of bridge collapse cases in history, analysis of which helps to understand the mechanics of the collapse process and find the design solutions, which are save and which are not, and take this experience in consideration in design of new bridges or maintenance of existing bridges.

One of the common preventable causes of bridge collapse is accidental impacts of vehicles. Firstly, the probability of such an impact should be minimized whenever possible, that is, the bearing elements should be located at a distance from the zone of possible impact or systems like the laser clearance gates should be used, where the risk of hit is high. If it is impossible to remove the element from the impact zone, then it must be designed for accidental impacts. Thin pillars of supports in navigable waters should be avoided, even if they are not on the navigable route.

Progressive collapse has the greatest consequences; therefore, it is important to design bridge structures resistant to progressive collapse as much as possible. In general, this can be achieved by increasing the robustness of structure or localizing the failure.

Robustness is the main component of reliability, hence, critical nodes and elements, on the integrity of any of which the stability of the entire structure depends, should be avoided. Instead, efforts should be distributed over several similar elements, which can take an extra load in case of failure of any one of them. These elements should be combined into a system that ensures the redistribution of efforts. Nevertheless, local failures must be prevented. A significant part of bridge collapses occurs due to untimely detection and elimination of critical structural defects; therefore, all load-baring elements of structure must be available for inspection and repair.

References

@GDOT East Traffic. 2021. Tweet 15 July 2021. Twitter microblog service. Retrieved on 12 November 2022. Available at https://twitter.com/GDOTEastTraffic/status/1415628773488222211

Billington, D., Hubert, S. & Billington, P. Bridge. Encyclopaedia Britannica. Accessed on 15 October 2022. Available at https://www.britannica.com/technology/bridge-engineering/The-Middle-Ages

Dela.ru. 2014. Report 7 July 2014. Retrieved on 12 November 2022. Available at https://dela.ru/news/obrushenie-viaduka/

Dorinfo. 2022. Report 27 May 2022. Retrieved on 12 November 2022. Available at https://dorinfo.ru/star_detail.php?ELEMENT_ID=117077

Encyclopedia Britannica. Image of Old London Bridge. Retrieved on 15 October 2022. Available at https://www.britannica.com/topic/Old-London-Bridge#/media/1/347007/6416

Encyclopedia Britannica. Image of Pont de la Concorde. Retrieved on 15 October 2022. Available at https://www.britannica.com/place/Place-de-la-Concorde#/media/1/131252/185402

Eremin, K., Mahutov, N., Pavlova, G. & Shishkina, N. 2011. Register of accidents of buildings and structures 2001–2010. Magnitogorsk: Magnitogorsk Printing House.

Guojing, Z., Yongjian, L., Jiang, L., Shiyong, L., Jian, Y. 2022. Causes and statistical characteristics of bridge failures: A review. Journal of Traffic and Transportation Engineering (English Edition), June 2022, 388-406. Retrieved on 6 November 2022. Available at https://www.sciencedirect.com/science/article/pii/S209575642200040X

Interfax. 2011. Report 3 November 2011. Retrieved on 12 November 2022. Available at https://www.interfax-russia.ru/ural/view/gruzovik-protiv-mosta

Interfax. 2016. Report 1 July 2016. Retrieved on 12 November 2022. Available at https://www.interfax.ru/photo/2835/30930

Johnson, B. Ironbridge. Historic UK. Accessed on 15 October 2022. Available at https://www.historic-uk.com/HistoryMagazine/DestinationsUK/Ironbridge/

Kalmikov, N. 1957. Stone and concrete bridges and culverts. Moscow: Scientific and technical publishing house of motor transport literature.

Karavanskiy, A. 2015. Russian Ministry of Internal Affairs for the Orenburg Region. Report 13 December 2015. Retrieved on 12 November 2022. Available at https://56.xn--b1aew.xn--p1ai/news/item/6905896/

Lazarova, D. 2017. Collapse of Prague footbridge raises concerns regarding state of other bridges. Radio Prague International. Report 12.04.2017. Retrieved on 15 November 2022. Available at https://english.radio.cz/collapse-prague-footbridge-raises-concerns-regarding-state-other-bridges-8174969

Mattioli, G. 2019. What caused the Genoa bridge collapse – and the end of an Italian national myth? The Guardian, 26 February 2019. Retrieved on 13 November 2022. Available at https://www.theguardian.com/cities/2019/feb/26/what-caused-the-genoa-morandi-bridge-collapse-and-the-end-of-an-italian-national-myth

Mizzy, S. 2022. The case of the collapsed Troja Bridge will go to court again, the plaintiff appealed. Europe-cities. Report 29.04.2022. Retrieved on 15 November 2022. Available at https://europe-cities.com/2022/04/29/the-case-of-the-collapsed-troja-bridge-will-go-to-court-again-the-plaintiff-appealed/

Ovchinnikov, I.I., Valiev, S., Ovchinnikov I.G., Shatilov, I. 2020. Accidents of transport facilities and their prevention. Cheboksary: Publishing House “Sreda”.

PERI. Image of balanced concreting technology. Retrieved on 15 October 2022. Available at https://www.peri.no/om-peri/press/kicevo-podvis-motorway-bridge.html

Protectnepa. Image of I-40 bridge collapse. Retrieved on 12 November 2022. Available at https://protectnepa.org/transportation-and-infrastructure/i40-bridge-collapse-oklahoma/

Reimann, M. 2017. The deadliest bridge disaster in US history was caused by a tiny crack just three millimeters deep. Timeline. Retrieved on 21 November 2022. Available at https://timeline.com/the-deadliest-bridge-disaster-in-us-history-was-caused-by-a-tiny-crack-just-3-millimeters-deep-ca5404c4dffa

Salamaxin, P. & Popov, V. 2017. Road and city bridges in Russia. Moscow: Madi.

SFS-EN 1990. 2002. Eurocode. Basis of structural design. Helsinki: Finnish standard association SFS.

SFS-EN 1991-1-7. 2022. Eurocode 1. Actions on structures. Part 1-7: General actions. Accidental actions. Helsinki: Finnish standard association SFS.

Syrkov, A. 2021. Defects in load-bearing structures of steel and steel-reinforced concrete superstructures. Lecture recorded at SPbSUACE on 02.12.2021.

Telegram. 2014. Report 28 May 2014. Retrieved on 12 November 2022. Available at https://www.telegram.com/story/news/2014/05/28/laser-system-could-solve-truck/37235545007/

Tengrinews. 2019. Report 24 August 2019. Retrieved on 12 November 2022. Available at https://tengrinews.kz/kazakhstan_news/obrushenie-mosta-pavlodarskoy-oblasti-voditelya-gruzovika-377397/

The Open University. Figure of structure of critical eye-bar joint. Retrieved on 21 November 2022. Available at https://www.open.edu/openlearn/science-maths-technology/engineering-technology/introduction-structural-integrity/content-section-3.3.5

Ural-meridian. 2020. Report 26 October 2020. Retrieved on 12 November 2022. Available at https://ural-meridian.ru/news/261808/

West Virginia & Regional History center. Image of Silver bridge.

Wolf, M. & Starossek, U. 2009. Cable loss and progressive collapse in cable-stayed bridges. Bridge structures 5.1 (2009): 17–28.

Yle. 2010. Report 22 November 2010. Retrieved on 12 November 2022. Available at https://yle.fi/news/3-5674261

Zhao, K., Song, Y. & Wang, J. 2014. Progressive collapse mechanism of continuous girder bridges under barge collision. The 2014 World Congress on Advances in Civil, Environmental, and Material Research (ACEM14). Retrieved on 17 November 2022. Available at http://www.i-asem.org/publication_conf/acem14/6.ACC/T5F.1.CC403_917F.pdf

T.K.M. Image of Old Voroshilovskiy bridge in Rostov-on-Don. Retrieved on 17 November 2022. Available at https://www.tkm-most.ru/projects/project-monitoring/voroshilovskiy-most-staryy-v-g-rostov-na-donu/