Actual quantification of probabilities for selected bridge failure scenarios

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Abstract: Considering risk analysis for civil structures, it is essential to determine the possible course of failure. There are numerous scenarios of different likelihood of occurrence. Several scenarios of the failure of bridge structures are proposed in the paper. Moreover a brief analysis of three failure scenarios for the stays of cable-stayed bridges is presented. The analysis applies to modern 21st century bridges built using state-of-the-art technologies. These are bridges with 60 ÷ 375 m long cable-stayed spans. As a result of the analysis, the probabilities of the occurrence of failure events were estimated. The considered scenarios should influence the layout of a structural monitoring system, if such system was proposed for the bridge.

1. INTRODUCTION FAILURE SCENARIOS AND RISK ANALYSIS

Civil structures and their users are subjected to various hazards, which can be considered within the risk analysis. A risk analysis covers the following: identifying hazards and determining scenarios of events, estimating the probability of the occurrence of the events, determining the expected effects, assessing the risk (acceptability), and considering preventive measures. All those factors were discussed in the works of Vrouwenvelder et al.[1] , Faber [2], Faber and Stewart [3], and code ISO [4].

After the scenarios of failure situations are formulated, the probability of the occurrence of an event resulting in a failure situation should be determined. Failure scenarios include a large number of factors connected to load and structural resistance, which should be selected by an expert. In the case of environmental loads, such as the wind load, there are often statistical data available which can be used to calculate the probability of the occurrence of a particular wind load. Similarly, there are statistical data on the service loads supplied by the existing monitoring systems, including measurements of vehicle weight in motion. It should be mentioned that not only the weight of a vehicle is easy to measure, but also its position along the bridge can be found. Examples were presented in the works of Machelski and Hildebrand [5, 6].

Failure scenarios formulated on the basis of standard loads are not the key ones. In the design of a bridge, various loads (the values of which are specified in standards or other documents) are taken into account. The probability of failure resulting from the action of standard loads is relatively low – in the order of 10⁻⁵. This means that in the case of typical (in their form and size) civil structures, “standard” scenarios do not shed any new light on their structural safety. Therefore, there is a need to record and analyse failure events pertaining to all civil (bridge) structures, which have happened in the
world to make the database of failures fully reliable.

2. METHODS OF JUXTAPOSITION OF FAILURE FACTORS AND SCENARIOS

In the case of bridges, the following events or processes regarded as leading to failure situations can be indicated:

- a change (deterioration) in the characteristics of structural materials,
- rheological phenomena (shrinkage, creep, relaxation),
- corrosion,
- fatigue,
- highly repeatable loads and deformations,
- excessive strains (stresses),
- environmental (wind, ice floe, water wavy motion, river current, etc.) loads,
- leaks and the presence of water,
- unforeseen damage (accidents, vandalism, fires),
- geotechnical phenomena, earthquakes.

It is not always the case that the factors and the failure situation scenarios giving the impression of the greatest danger or being the most spectacular result in the highest risk. Some failure factors have an implicit character while other failure factors have an explicit and sometimes spectacular character. Depending on the way they affect the civil structure, failure factors can be divided into: long-duration factors and short-duration (sudden) factors.

Some failure factors and scenarios are shown in Table 1, from the previous author’s work [7]. The classification of the types of damage is based on Bien[8]. The main difficulty in developing failure scenarios useful for risk analysis is the determination of failure probability. Random events to which the constructed failure scenarios refer are characterized by a highly varied probability of their occurrence. However, risk analyses are based on the Bayesian interpretation of probability. Decisions are made on the basis of Bayes’ theory despite the insufficient number of experiments which could form the basis for estimating the frequency of occurrence of certain events. However, in some cases, the consideration of failure scenarios can be regarded as an a posteriori analysis, where the events have actually occurred and it is possible to estimate the assigned probability.

An exemplary a posteriori analysis is the consideration of a scenario for the failure of the stay of a cable-stayed bridge caused by a motor vehicle impact as a result of a car accident. Such events actually occur. The probability can be assessed on the basis of:

- the number of vehicle impact marks on bridge barriers
- CCTV surveillance,
- information supplied by city maintenance services, police, etc.

At least two serious vehicle collisions with barriers occurred along the whole length of a certain bridge in the years 2007-2012. Three sections of the barrier, each about 10 m long, suffered substantial damage. In one of the cases, during the crash, the car hit the barriers twice. The length of the cable-stayed part of the bridge amounts to 615 m and the total length of the crossing amounts to 1700 m. There are two roadways on the bridge and the cable stays are situated in the median strip. The total length of the barriers on the bridge amounts to 1700×4=6800 m. Thus, 3×10/6800 = 0.0044 of the barriers have suffered damage over 5 years. For the bridge service life of 100 years, probably (100/5)×0.0044 = 0.088 part of the bridge barriers will undergo damage. This means that the probability of damage to any fragment of the barriers over 100 years amounts to 8.8%. Some of the barriers running near the lower sections of the cable stays constitute (2×615)/6800 = 0.362 of the total barrier length. Thus, the probability that the barrier running along the cable-stayed part will be damaged amounts to 0.088×0.362 = 0.03. It should be assumed that only every tenth impact may lead
to the destruction of the barrier. Hence, the probability that the impact will be so strong that it will break through the barriers and damage one cable stay amounts to 0.003 for the 100 years horizon.

A similar analysis can be performed for, e.g., vehicle fires on or under a bridge. Both, vehicle impacts on bridge elements and fires on bridges are events of sudden nature. However, there also occur long-duration factors, such as the corrosion hazard on the steel parts of the bridge.

| Type of damage | Failure factor | Exemplary failure scenarios and effects |
|----------------|---------------|----------------------------------------|
| Effects of long-duration processes | Excessive or uneven settlement of supports | - overloading and failure of bearings → no span support
- compression → buckling and failure of previously tensioned members
- decompression of prestressed segments → opening of joints |
| Deformations | Excessive rheological deflection of concrete span | - overloading of some members → breakage or rupture
- disturbed structure gradeline → derailment |
| | Excessive relaxation elongation of steel in external tendons | - loss of hydraulic gradient of the drainage system → pavement flooding |
| Material degradation | Excessive cracking of concrete | - corrosion of steel resulting in its loss → rupture or breakage of member |
| | Corrosion of steel | - section loss → rupture or breakage of member,
- corrosion of jaws → unfasten of tendon |
| | Carbonatation of concrete and other chemical processes | - damage to reinforcement cover → corrosion of reinforcement → reduction of load bearing capacity
- disintegration of concrete structure into separate members → disintegration of member
- reduction in concrete strength → loss of member load bearing capacity |
| Loss of material | Missing fragments of deck pavement | - disturbance in travel → traffic accident |
| | Missing fragments of expansion joint | - disturbance in driving → traffic accident
- shocks and overloads → damage to adjoining parts of structure |
| Loss of continuity | Breakage of tendon strands | - rupture of tendon → reduction in load bearing capacity or breakage of span |
| | Fatigue of member material | - loss of structural continuity → loss of stability, toppling of girders
- loss of connection (connectors, gusset plates) effectiveness → disturbance of static system with loss of structural stability |
| | Fatigue of improperly made pedestrian railing | - fracture and breakage of balusters → fall dawn of pedestrian |
| Contamination | Presence of water in cable anchorage | - corrosion of wedges and loss of anchorage reliability → loss of load bearing capacity or breakage of span |
| | Presence of water in cable duct | - corrosion of strands and their rupture → reduction in load bearing capacity or breakage of span
- filling with water of empty space resulting in
structure overload → reduction in available load bearing capacity of span → overloading and settlement of foundations

| Changes in position | Buckling of structural member | Change in stay sag |
|---------------------|-------------------------------|-------------------|
|                     | - Excessive amplitudes of      | - collision with  |
|                     | stay vibrations                | other elements,   |
|                     |                               | such as lighting, |
|                     |                               | clearance gauge,  |
|                     |                               | etc. → damage to |
|                     |                               | adjacent members,|
|                     |                               | collision with   |
|                     |                               | vehicle          |

Effects of sudden processes

| Deformations | Vehicle or vessel impact |
|--------------|--------------------------|
| - reduction in load bearing capacity as result of disturbance in member shape → reduction in load bearing capacity of span |
| - transverse shift of track on rail bridge → derailment |

| Material degradation | Fire |
|----------------------|------|
| - heating of material → reduction of load bearing capacity or breakage of span or its member |

| Loss of material | Vehicle or vessel impact |
|------------------|--------------------------|
| - loss of some of cross section or whole member → reduction in load bearing capacity or breakage of span |
| - collapse of structure → traffic disaster |

| Loss of continuity | Vehicle impact |
|--------------------|----------------|
| - loss of structural continuity → reduction in load bearing capacity or breakage of span |

| Contamination | Spillage of transported noxious agent onto structure |
|---------------|------------------------------------------------------|
| - loss of anti-slip properties of deck surface → traffic accident |
| - filling with water of space inside structure → depletion of load bearing capacity of structure |

| Changes in position | Landslides |
|---------------------|------------|
| - displacement of supports → hinge in vault → reduction in load bearing capacity or breakage of span |
| - displacement of supports → failure of span |

A failure of a steel load-bearing member due to corrosion is rather intuitive. However, it is difficult to determine the probability of its occurrence.

As a rule, modern cable-stayed bridges have cable stays consisting of steel strands individually anchored in wedges and the anchorage is of the mechanical (frictional) type. The place of anchorage is hidden under a tight cover (cap), the function of which is to eliminate the effect of the environment, mainly rain water. Surprisingly, it happens that water collects under the tight cover, somehow managing to penetrate into this protected space. Water poses a danger to the effectiveness (reliability) of the cable-stay anchorage and so it poses a risk to the proper functioning of this critical structural member.

The probability of water getting inside an anchorage can be estimated after surveying a larger number of anchorages after several years of service. In the case of two contemporary cable-stayed road bridges built in the same country in the 21st century thorough visual inspections and partial disassembly of the anchorage caps were carried out. It was found that water may appear in the lower anchorages (under the deck), whereas in the upper anchorages (in the towers) water does not stay. One of the investigated bridges was a composite over-bridge with a single tower and two 68 m long cable-stayed spans and a several beam spans while the other bridge was a road bridge with two towers and cable-stayed spans in the 60+60+375+60+60 m arrangement. The observations are for ten years of service of the bridges. In total, 73 anchorages in the two bridges were examined (Figure 1 and Figure 2).

Water was found to be present in 10 anchorages, i.e., 13.6% of all anchorages. It should be noted that
the presence of water is not sufficient to cause corrosion since the strands and anchorages are protected with a layer of zinc and a layer of petroleum wax, constituting additional barriers of the anticorrosion system. During the inspections of the anchorages it was found that only in one case symptoms of the beginning of the corrosion process were visible (on the outer surface of the wedges). This means that corrosion was initiated only in one of the 73 inspected anchorages, which amounts to 1.4% of all anchorages.

Figure 1. Lower anchorage without injection cap. The lack of injection wax is visible. The corrosion process is not in progress.

Figure 2. Inspection of pylon (upper) anchorages using an elevator.

Therefore, considering the population of 73 investigated anchorages, one can conclude that the probability of the onset of corrosion amounts to about 0.014, while the probability of the occurrence of corrosion advanced to a degree which poses a risk to the safety (reliability) of the anchorage is lower at least by one order of magnitude, amounting to 0.0014. It should be added that the above conclusion applies to a ten-year period of service of the bridges. Thus, for the period of one year, the probability of corrosion developing in one anchorage of one cable stay to a degree posing a hazard to safety amounts to about 0.00014, i.e., $1.4 \times 10^{-4}$, while for the period of 100 years this probability amounts to $1.4 \times 10^{-2}$. It should be underlined that the corrosion process embracing one or two strands is not in fact dangerous for the whole stay due to the mechanical independence of all strands in one stay. Finally, the probability of safety threats referring to the whole stay is lower than $1.4 \times 10^{-2}$ at least by 5 times, i.e. $1.4 \times 10^{-2}/5 = 0.003$ for the period of 100 years. (It was assumed that only 20% of the jaws in one anchorage are embraced by the corrosion process).

It is unquestionable that the probability of the occurrence of corrosion strongly depends on the quality (class) of the stay system members, the cable system operating conditions, and the level of bridge maintenance care.

Another kind of cable stay anchorage failure is a wedge failure caused by a wedge manufacturing or on-site assembly defect, in which case a strand may spontaneously unfasten. The probability of such an event is estimated at 0.0005 – referring to the whole lifespan of the bridge (based on the author’s own observations). If there are 50 strands in the cable stay, the probability that 10% (5 strands) of them will unfasten (which is tantamount to the impermissible regrouping of the forces in the cable stay) amounts to $P = 0.0005^5 \approx 3 \times 10^{-17}$ (provided the events are independent). It should be mentioned, however, that the strands usually spontaneously unfasten (if any) when they are assembled during the construction of the bridge (e.g., within a few days since the mounting of the wedges and tensioning the strands), that is why the above given probability relates to the period of ca. 100 years.

3. RECAPITULATION AND DISCUSSION

Selected scenarios of the failure of the stay system components of modern cable-stayed bridges were
analysed in detail on the basis of the author’s own observations. The results of the analysis are presented in Table 2.

### Table 2. Selected failure scenarios with estimated probability.

| No. | Failure scenario                                                                 | Factor                                                                 | Probability of failure during 100 years |
|-----|----------------------------------------------------------------------------------|------------------------------------------------------------------------|----------------------------------------|
| 1   | Rupture of or serious damage to cable stay above deck level                      | Vehicle impact against cable stay                                      | 0.003                                  |
| 2   | Loss of effectiveness (reliability) of anchorage in wedges                       | Hidden corrosion process inside anchorage                               | 0.014                                  |
| 3   | Impermissible regrouping of forces in cable stay due to loss of effectiveness of anchorage in wedges | Defect in anchoring wedges, manufacturing defect or assembly error      | \(10^{-17}\)*                          |

*) The assumed number of strands in the cable stay – 50 units.

It should be noted that the occurrence of the above failure situations can be determined with the assistance of bridge monitoring systems. Some examples were given in the works of Karbhari [9] and Kurata[10]. Specific indicators, e.g., water presence sensors indicating a corrosion hazard, can be used in inaccessible places in the bridge structure. If need be, also force sensors can be used to observe the average values of the forces in the cable stays over a long period of time, as well as specialist sensors detecting sounds originating from the structure, which may help to detect sudden incidents of the redistribution of forces in the cable stays. In the case of the progressing degradation of the structural load-bearing members, its effect in the form of the weakening of cross sections (material loss) can be monitored in direct relation to the structure’s load-bearing capacity through the modelling of the appropriately reduced cross sections as presented by Maksymowicz et al. [11].

### 4. CONCLUSIONS

There are a lot of different failure scenarios for bridges, however, it is possible to quantify the actual probability of selected failures on the ground by detailed observations taken during maintenance activities or via monitoring systems.

Thus, the thorough monitoring of the existing bridges and the recording of various events occurring during their service form the basis for the estimation of the appropriate probabilities. It should be emphasized that the probability of the occurrence of a failure event is not by any means tantamount to the collapse of the bridge. A failure of one element usually does not have to result in the destruction of the whole bridge structure. The consideration of a potential collapse of the whole structure should be based on an analysis of its static diagram and should be undertaken already at the design stage.

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