Analysis of a Damaged Bridge Object as a Result of Vehicle Impact

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Abstract. The article presents a case of damage to an object caused by an impact of vehicle or load. The bridge over the expressway has a typical structure used in Poland in the 70's and 80's of the last century. Spans were made of Płoński beams (T beams) joined only by locks at the junction of the upper beams' flanges. As a result of impact with the vehicle / load, there was a horizontal crack at the contact of the web with the top flange almost along the entire length of the beam. Visible stirrup deformation indicates complete loss of cooperation between beam elements at the point of impact. The part of strands were also broken. The method of estimating the load capacity of a damaged beam is discussed and the temporary protection of a damaged beam and recommendations for further handling of the bridge are presented.

1. Introduction

In bridge construction, prefabricated prestressed concrete beams are widely used. The advantage of such solutions is the ability to achieve very high quality of these elements due to the production under controlled conditions in the factory. We are able to achieve greater accuracy of execution and reduction of the impact of a variable environment on the materials from which they are made. Serial production of these elements also allows maximum optimization of solutions, including above all the cross-section of prefabricated elements. In the case of construction, the use of these solutions allows you to accelerate work on the construction site, reduce the amount of formwork and temporary supports needed. These advantages are especially evident when overcoming water obstacles or active communication routes. In this case, we also reduce the social costs of construction associated with restrictions caused by the investment. These advantages mean that sometimes, despite the higher purchase and transport costs compared to the cost of in-situ components, the solution turns out to be globally more beneficial.

The disadvantage of solutions is, in the case of beam bridge structures, low resistance to side impact. Impact of the vehicle on the beam can cause very large and costly repair.

2. The problem of side impacts in prefabricated beam bearing systems

In the case of smaller spans, the prefabricated elements are assembled into a slab load-bearing structure, while in the case of larger spans, T or I beams are used. Due to the number of prefabricated elements, the greatest possible optimization of this type of beams is sought. This is achieved by using the smallest cross-section of the beams with simultaneous increase in height to maximize the use of the prestressing arm. In addition to less material consumption, additional benefits are associated with the reduction of the weight of prefabricated elements, which facilitates and reduces transport costs. Such optimization leads
to a similar cross-section of various solutions - in the case of T-beams, we have a wide upper flange in order to reduce the amount of in-situ formwork needed and to obtain a large area of connection with the concrete, the high and very narrow web widened in the lower part only to the extent necessary for arrangement of compression strands. For type I beams, instead of the wide upper flange, a slight widening of the web is used only to the extent necessary to obtain the minimum necessary connection surface to ensure composite action. In addition, bridge design solutions using these beams for maximum cost and construction time reduction do not use span, but sometimes support cross beams. This solution results in very low load capacity when a horizontal load is applied to the bottom of the beam. This is the basic minus of such a solution in the event of impacts caused by transporting loads under objects of too high height (in the event of non-compliance with traffic restrictions or poor load securing, e.g. not lowering the arms of construction equipment during transport). In this case, impacts to the bottom of the beams cause very big damage, sometimes destruction of the beams. Repair costs for damaged beams are very high. An additional problem is determining how to repair beams. In the event of significant damage, it is necessary to determine the stress level of the element in order to choose the correct repair method. The level of compression in the event of an impact will depend on the change in the cross-section (loosening of the concrete fragment, division of the cross-section into independent parts) and damage to the strands (broken strands). Incorrect estimation of the stress level may lead to improper beam strengthening or repair, which may result in object failure [1].

3. General characteristics of the object
The viaduct which was damaged due to vehicle (load) impact was made of the prefabricated span system of the "Płońsk" type of prestressed concrete beams, very popular in Poland in the 70s and 80s. In this system, theoretical spans of 14.5 m, 17.5 m, 20.5 m and 23.5 m could be obtained. Beams of the "Płońsk" system were T-beams (figure 1) [2].

![Figure 1. Cross-section of a "Płońsk" beam with a length L = 18.0 m](image)

The viaduct is a four-span freely supported. The superstructure is made of prefabricated beams of the "Płońsk" type. "Płońsk" type beams with a length L = 18.0 m were used in two central spans. Concrete beams with the length L = 9.0 m were used in the extreme span. The beams were made in the form of "Płońsk" beams L = 18.0 m. They have the same cross-sectional dimensions as the beams L = 18.0 m. "Płońsk" beams have bottom flange 48 cm wide and upper flange 120 cm wide. The height of the beams is 94 cm. The beams were joined by filling the locks. No concrete topping was used. A layer of leveling concrete with a thickness of from approx. 4 cm to approx. 10 cm above the support was used. The differences in the thickness of the leveling layer result from the reverse arrow of the prestressed beams. In the cross section of the object there are 7 beams with a spacing of 1.50 m. Crossbeams are only on the supports. They were made on site in the form of beams with a cross section of 62 cm x 110 cm – figure 2, 3, 4. The overall width of the superstructure is 10.80 m – figure 3.
Supports are monolithic. Intermediate supports are pillars in the form of crown beam and round reinforced concrete columns (three in each pillar). The external supports are abutments in the form of a crown beam and probably three round reinforced concrete columns.

![Figure 2. Side view of the viaduct](image)

![Figure 3. Cross section of the viaduct](image)

![Figure 4. General view of the viaduct](image)

4. **Characteristics of damage caused by vehicle / load impact**

Damage caused by vehicle impact was found in the case of the outer beam of one of the central spans – figure 5 to 12. As a result of the impact there was a horizontal crack in the beam at the connection with the upper flange – figure 11, 12. At the crack, shear reinforcement was plastified around the point of impact. The beginning of this crack was found at a distance of 1.68 m from the crossbeam on one pillar, the end at a distance of 2.27 m from the crossbeam on the second pillar. In addition, at the point of impact, the fragments of the concrete of the lower shelf detached and two strands were broken and one strand was exposed from the outside, and four were broken, one strand was damaged and the three
strands were exposed from the inside of the beam. On the left side of the place of damage, the bottom shelf was diagonally cracked and some concrete was loose. One strand was partially exposed. In addition, numerous diagonal cracks were found on the side surface of the beam and its bottom.

Figure 5. Side view. On the outer beam visible damage

Figure 6. Bottom view. On the outer beam visible damage. Exposed reinforcement and loss of beam material visible. Concrete cracking is visible along the entire beam width

5. Analysis of the impact of damage on internal forces and stresses
In order to assess changes in internal forces in the beam elements of the damaged span, a static analysis was performed. For this purpose, the span was modelled as a grate, in which longitudinal bars were prefabricated beams with real rigidity. In the case of a damaged beam, its rigidity was reduced to take account of damage. It was assumed that as a result of the crack, the upper flange and web together with the lower flange are independent elements, and the stiffness of the bar in the grate corresponds to the sum of the stiffness of these elements. It was assumed that internal forces would be transferred only by the lower, prestressed part of the damaged beam. This is a safe assumption. The transverse bars have rigidity corresponding to the slab and cross member.
Figure 7. Bottom view of the damaged beam. Diagonal cracks are visible on the bottom of the beam.

Figure 8. View of the beam from the inside. Significant losses of beam material are visible, as well as exposed, torn off and corroded reinforcement and prestressing strands of the beam.

Figure 9. View of the beam from the outside. Significant losses of beam material are visible, as well as exposed, torn off and corroded reinforcement and prestressing strands of the beam.
Figure 10. View of the beam from the outside. The beam reinforcement is exposed. Cracks are visible along the entire height of the beam.

Figure 11. View of the beam from the outside. Horizontal cracks are visible at the web connection with the upper flange and exposed and deformed transverse reinforcement.

Figure 12. Beam damage caused by impact – side view.

Due to the safe assumption of lack of cooperation between the upper flange and the remaining part of the beam along the entire length of the crack and small stresses in the upper shelf in the unusable state, the effect of changing the state of stresses in the damaged beam on internal forces was omitted. The changes were very small. The beams are connected only by the locks. They have a width of 30 cm and a height corresponding to the height of the upper flange of prefabricated beams. At the time when the viaduct was built, the quality of the concrete made at the construction site was very low. This plus
the relatively small dimensions of the locks meant that the quality of concrete in this type of elements is very low. Due to large differences in the rigidity of the material of the locks and prefabricated beams, the impact of composite action between beams and locks was omitted in the calculations.

Static calculations were made assuming loads according to code PN-85/S-10030 [3]. To determine the internal forces for individual load classes according to the standard [3], the forces obtained for class A load were multiplied according to appropriate factors.

As a result of calculations, bending moments in the damaged and adjacent most strained beams before and after the occurrence of damage are summarized in Table 1. The calculations also took into account the maximum narrowing of the road in order to maximally relieve the damaged beam while maintaining the possibility of passing through the object.

**Table 1.** Values of characteristic bending moments for class A load according to the standard [3]

|                      | Self weight | Additional dead weight | Crowd pedestrians load | The car rolling stock load evenly distributed | The car rolling stock point load |
|----------------------|-------------|------------------------|------------------------|---------------------------------------------|----------------------------------|
| Adjacent beam in relation to the damaged in the absence of damage, center of span | 446.0 kNm    | 460.1 kNm        | 34.1 kNm           | 151.6 kNm                                  | 699.3 kNm                      |
| Damaged beam after damage, center of span | - no narrowing of the road | - | - | - | - |
| 133.8 kNm             | 179.7 kNm   | 15.4 kNm              | 29.5 kNm            | 134.8 kNm                                  |
| 133.8 kNm             | 179.7 kNm   | 0.1 kNm               | 5.6 kNm             | 25.6 kNm                                   |
| Damaged beam after damage, place of damage to the strands | - no narrowing of the road | - | - | - | - |
| 129.7 kNm             | 173.2 kNm   | 14.8 kNm              | 29.0 kNm            | 131.3 kNm                                  |
| 129.7 kNm             | 173.2 kNm   | 0.1 kNm               | 5.9 kNm             | 26.6 kNm                                   |
| Adjacent beam in relation to the damaged one after the damage, center of span | - no narrowing of the road | - | - | - | - |
| 622.7 kNm             | 694.5 kNm   | 54.0 kNm              | 191.8 kNm           | 868.2 kNm                                  |
| 622.7 kNm             | 694.5 kNm   | 32.0 kNm              | 134.6 kNm           | 704.2 kNm                                  |

The table shows that the reduction in stiffness of the damaged beam caused a significant redistribution of forces on adjacent elements, primarily on the adjacent beam, which after the damage is the most intense beam of the superstructure.

Stress checking in the elements was carried out in accordance with code PN-91/S-10042 [4]. In addition to checking the stress, the cracking moments were also checked. In the case of a damaged beam, the check was made taking into account the new, reduced cross-section after damage - the top flange was omitted. Additionally, the change in prestressing force caused by the change in the cross-section of the prestressed element was taken into account. In the place of damage to the strands, additional reduction of the prestressing force by removing the strands from work was taken into account. The exclusion of strands from work was taken into account for the length of the damage and for a length equal to the length of the anchorage on both sides of the damage to the strands [5]. The analysis also took into account asymmetrical string damage by taking into account horizontal bending caused by the emergence of an eccentric force in this direction. Obtained stresses and cracking moments are summarized in tables 2 to 5.
Table 2. Stresses and cracking moments in the most stressed beam in the absence of damage, determined according to the standard [4]

| Load class | State       | Fibers | Stresses / Characteristic moment *sR | Permissible stresses / Cracking moment | Exceeding of [%] |
|------------|-------------|--------|--------------------------------------|----------------------------------------|------------------|
|            | initial     | upper  | 1,1 MPa                              | -2,1 MPa                               | -                |
|            |             | lower  | 20,9 MPa                             | 25,6 MPa                               | -                |
| Class C    | nouseable   | upper  | 4,8 MPa                              | -2,1 MPa                               | -                |
|            |             | lower  | 15,0 MPa                             | 23,1 MPa                               | -                |
|            | usable      | upper  | 16,7 MPa                             | 23,1 MPa                               | -                |
|            |             | lower  | 1,5 MPa                              | -2,1 MPa                               | -                |
|            | cracking    |        | 1708,2 kNm                           | 1823,1 kNm                             | -                |

Table 3. Stresses and cracking moments in the most strenuous beam of undamaged beams after damage, determined according to the standard [4]

| Load class | State       | Fibers | Stresses / Characteristic moment *sR | Permissible stresses / Cracking moment | Exceeding of [%] |
|------------|-------------|--------|--------------------------------------|----------------------------------------|------------------|
|            |            |        | - no narrowing of the road           |                                        |                  |
| Class C    | nouseable   | upper  | 8,2 MPa                              | -2,1 MPa                               | -                |
|            |             | lower  | 9,9 MPa                              | 23,1 MPa                               | -                |
|            | usable      | upper  | 23,1 MPa                             | 23,1 MPa                               | -                |
|            |             | lower  | -6,2 MPa                             | -2,1 MPa                               | 195,2            |
|            | cracking    |        | 2353,6 kNm                           | 1823,1 kNm                             | 29,1             |
| Class D    | nouseable   | upper  | 8,2 MPa                              | -2,1 MPa                               | -                |
|            |             | lower  | 9,9 MPa                              | 23,1 MPa                               | -                |
|            | usable      | upper  | 21,5 MPa                             | 23,1 MPa                               | -                |
|            |             | lower  | -4,37 MPa                            | -2,1 MPa                               | 108,1            |
|            | cracking    |        | 2199,0 kNm                           | 1823,1 kNm                             | 20,6             |
| Class E    | nouseable   | upper  | 8,2 MPa                              | -2,1 MPa                               | -                |
|            |             | lower  | 9,9 MPa                              | 23,1 MPa                               | -                |
|            | usable      | upper  | 20,0 MPa                             | 23,1 MPa                               | -                |
|            |             | lower  | -2,54 MPa                            | -2,1 MPa                               | 21,0             |
|            | cracking    |        | 2044,4 kNm                           | 1823,1 kNm                             | 12,1             |
Table 4. Stresses and cracking moments in a damaged beam after damage in the middle of the span, determined according to the standard [4]

| Load class | State          | Fibers | Stresses / Characteristic moment *sR | Permissible stresses / Cracking moment | Exceeding of [%] |
|------------|----------------|--------|--------------------------------------|----------------------------------------|------------------|
|            | - no narrowing of the road |        |                                      |                                        |                  |
| Class D    | usable          | upper  | 17,8 MPa                             | -2,1 MPa                               | -                |
|            |                 | lower  | 19,1 MPa                             | 23,1 MPa                               | -                |
|            | usable          | upper  | 37,3 MPa                             | 23,1 MPa                               | 61,5             |
|            |                 | lower  | 9,35 MPa                             | -2,1 MPa                               | -                |
| Class E    | usable          | upper  | 35,7 MPa                             | 23,1 MPa                               | 54,5             |
|            |                 | lower  | 10,12 MPa                            | -2,1 MPa                               | -                |
|            | usable          | upper  | 17,3 - 4,1 = 13,2 MPa               | -2,1 MPa                               | -                |
|            |                 | lower  | 16,4 + 4,1*1,2 = 21,3 MPa           | 23,1 MPa                               | -                |
|            | usable          | upper  | 34,2 + 4,1*1,2 = 39,1 MPa           | 23,1 MPa                               | 69,3             |
|            |                 | lower  | 8,06 - 4,1 = 3,96 MPa               | -2,1 MPa                               | -                |
|            | usable          | upper  | 433,6 kNm                            | 686,5 kNm                               | -                |

Table 5. Stresses and cracking moments in a damaged beam after damage at the place of strands damage, determined according to the standard [4]

| Load class | State          | Fibers | Stresses / Characteristic moment *sR | Permissible stresses / Cracking moment | Exceeding of [%] |
|------------|----------------|--------|--------------------------------------|----------------------------------------|------------------|
|            | - no narrowing of the road |        |                                      |                                        |                  |
| Class E    | usable          | upper  | 17,3 - 4,1 = 13,2 MPa               | -2,1 MPa                               | -                |
|            |                 | lower  | 16,4 + 4,1*1,2 = 21,3 MPa           | 23,1 MPa                               | -                |
|            | usable          | upper  | 34,2 + 4,1*1,2 = 39,1 MPa           | 23,1 MPa                               | 69,3             |
|            |                 | lower  | 8,06 - 4,1 = 3,96 MPa               | -2,1 MPa                               | -                |
|            | usable          | upper  | 433,6 kNm                            | 686,5 kNm                               | -                |

Analysis of the above tables shows that the biggest problem is a damaged beam. In the case of other elements, narrowing the road would allow the passage of cars with mass as before. Unfortunately, in the event of a damaged beam it does not provide an adequate level of safety. In the upper fibers of the damaged cross-section, the design compressive stresses are significantly exceeded in relation to the permissible ones.

6. Results and discussions

Recommendations for further handling of the viaduct took into account the current use of the object. The viaduct is located along a local road leading to the forest complex. It is not generally available. Only forest services and the Fire Brigade could use the facility.
General recommendations also took into account the condition of the object, which was not described in detail in this article. Due to the condition of the object and damage caused by the impact of the vehicle, the need for general renovation or reconstruction of the object was indicated. As part of the work, it was recommended to replace the damaged beam or, due to sporadic use of the object, to narrow the object by removing the damaged and outer beams in the axis of the damaged beam.

Decisions regarding further handling of the bridge and preparation for renovation works is a long-term process. The object, due to the insufficient load capacity of the damaged beam, requires immediate closing and repair of the beam. In order not to close the structure and not to bear the costs of repairing the beam, which would mostly cover lost works due to the recommended renovation or reconstruction of the structure, the possibilities of immediate lowest cost protective works were analyzed.

The main problem in the case of a damaged beam is the compressive stress in the upper fibers. According to the standard [4], they are checked in ultimate limit stages for the design values of forces. In this case, the allowable stress is significantly exceeded, which would require a wide range of protective work. To avoid this and minimize costs, stress from characteristic loads was checked. In this case, much lower stresses were obtained in the range of allowable stresses in concrete (for class E loads). Therefore, it was decided to narrow the road to minimize the transfer of loads to the damaged beam. In addition, it was recommended to make an injection of the cracks and suspension of the beam, which is to take over the weight of the beam in the event of further damage and to protect the structure against disaster. The suspension solution is shown in figure 13.

![Figure 13. The way of securing the beam by hanging it](image)

7. Conclusions
In the event of damage to prestressed structures, the biggest problem in repair / strengthening is estimating the stress level. The first problem is to determine how the prestressing force has changed, which will be related to damage to the compression itself, change in the cross-section of the beam, and redistribution of forces. It is especially difficult in the case of prestressed concrete, in which we are not able to measure the strength in the strands. In addition, especially for older constructions, there is no accurate information on the prestressing force introduced. Usually we use catalog data [2], however they may differ from real prestressing forces. This causes that the estimation of the state of stresses of the structure is uncertain. Therefore, in order not to damage the structure by improper strengthening, it is advisable to estimate the stress state on the safe side.
References

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