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# Vertical displacement of collapsed bridge in Palau

Sıddık Şener [a,*], Yasin Çağlar [b], Mehmet Akif Benzer [c], Kadir Can Şener [d]

[a] Department of Civil Engineering, İstanbul Bilgi University, 34060 İstanbul, Turkey
[b] Department of Civil Engineering, Kırıkkale University, 71451 Kırıkkale, Turkey
[c] 3DM Engineering & Consulting Co., 03200 Afyonkarahisar, Turkey
[d] Department of Civil Engineering, Purdue University, Indiana 47907-2045, USA

**ABSTRACT**

Vertical displacement of the Korror-Babeldaop (KB) Bridge in Palau is presented. This bridge was built in 1977 by the cantilever method and collapsed 3 months after remedial prestressing in 1996. KB Bridge was a segmental prestressed concrete girder having the world record of 241 m and maximum girder depth of 14.17 m. The final mid-span deflection was in design expected to be 0.53 to 0.65 m but after 18 years it reached 1.39 m and was still increasing. With a very limited amount of official information of the bridge was available and bridge was analyzed by ANSYS finite element program. Presented is an accurate analysis using 5392 hexahedral three-dimensional (3D) finite elements with 9614 nodes by ANSYS. Hognestad concrete model and Solid 65 element type were considered. The actual vertical displacements of free end of the cantilever bridge under truck loading were compared with the 3D finite element analyses results in order to come up with a benchmark model. The collapse reasons of KB Bridge were discussed.

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## 1. Introduction

The collapse of a record 240.8m long clear-span prestressed-concrete bridge after being in service for 18 years, in the Pacific island nation of Palau, occurred without any failure indications in 1996. Koror-Babeldaob Bridge was connecting Koror, Babeldaob Islands. The failure of the KB Bridge in Fig.1, occurred on 26 September 1996, at around 5.45 afternoons (Burgoyne and Scantlebury, 2006). The collapse of record span bridge (Yee, 1979) was catastrophic, killing two people and injuring four more, and occurred under virtually no traffic load during benign weather conditions. Services passing through the bridge between the country's two most populated islands were severed; this caused the government to declare a state of national emergency and request international aid for the thousands of people left without fresh water or electricity.

The main span was flanked by 72.2 m long end spans in which the box girder was partially filled with rock ballast to balance the moment at the main pier. The total length of the bridge was 386 m (Fig. 1). The thickness of the bottom slab varied from 1.15 m at the main piers to 0.18 m at the span. The web thickness of bridge was 0.36m in the main span. The cross section and hinge are shown in Fig. 2.

The two symmetric concrete box cantilevers that formed the main center span were each constructed simultaneously by 25 cast-in-place segmental section (Şener, 2006) 3.66 m depth at the mid-span hinges and 14.17 m deep over the main piers. The whole bridge was completed within in 2 years. There are so many researches on the reason of collapse of Palau Bridge going on (Bazant et al., 2009; McDonald et al., 2004; Pilz, 1997; Şener et al., 2009; Benzer, 2011).

The present study was undertaken to ascertain whether there is something fundamentally wrong with the way prestressed concrete is understood and in particular whether it should be thought differently in the light of what happened.

* *Corresponding author*. Tel.: +90-212-3117376 ; Fax: +90-212-4278270 ; E-mail address: siddik.sener@bilgi.edu.tr (S. Şener)

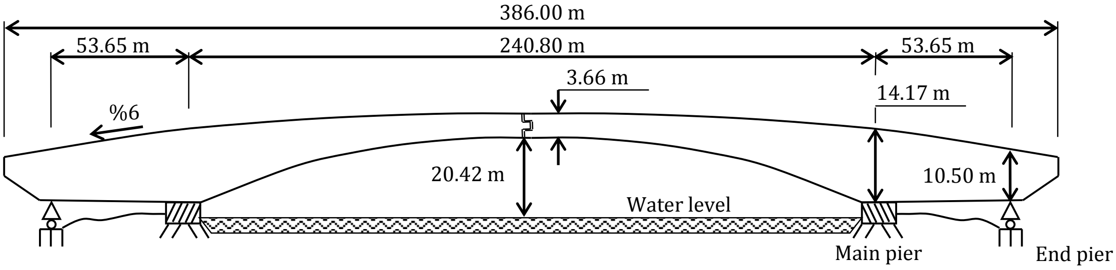


**Fig. 1.** Elevation of bridge geometry.

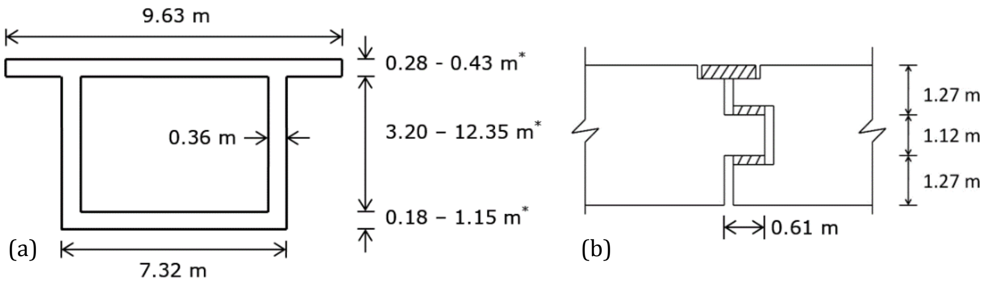


**Fig. 2.** a) Cross section of box girder at main pier, and b) hinge at the center of mid span.

## 2. Research Significance

Clarification of the causes of major disaster has been, and will always be, the main route to progress in structural engineering. Understanding of the excessive deflections of the bridge in Palau has the potential of greatly improving the predictions of creep and shrinkage effects in bridges as well as other structures.

## 3. Bridge Descriptions

According to design, the initial total longitudinal prestressing force above the main pier was 182.4 MN (≈0.70×316×812×1050 N), and was provided by 316 parallel high-strength threaded bars of diameter 32 mm and strength 1050 MPa (Fig. 3). Effective prestress was assumed as a $f_{ef}$=0.7$f_y$. The mass density of concrete was $\rho$=23.25 kN/m$^3$. Top slab covered by concrete pavement of average thickness 75mm. The aggregate was crushed basalt rock of maximum aggregate size about 19 mm, supplied from a quarry on the island of Malakal. The bars (the ducts of diameter 47.6 mm, later injected by grout) were placed in up to four layers within the top slab. Extended by couplers and anchored near the abutment, the prestressing bars had the diameter 32 mm and run continuously up to the segment of the main span at which the threaded ends were anchored by nuts. Threaded bars lengths in longitudinal direction were changing from 1.6 m to 18.3 m (7 different length).

From the fact that the erection took about 6 month, it is inferred that each fresh front segment was about 7 days old when prestressed. Generally tendons lengths less than 80 m were stressed from one end, longer than 80m were stressed from both. Threaded bars, of diameter 32 mm, and length 9.14 m were used to provide vertical prestress of the webs (spacing from 0.3 m to 3 m) and horizontal transverse prestress of the top slab (typical spacing is 0.56 m). The Young`s modulus of prestressing steel was assumed as 210 GPa and Poisson`s ratio as 0.3. In post-collapse examination, neither the prestressed nor the unprestressed steel showed and signs of corrosion, despite the tropical marine environment.

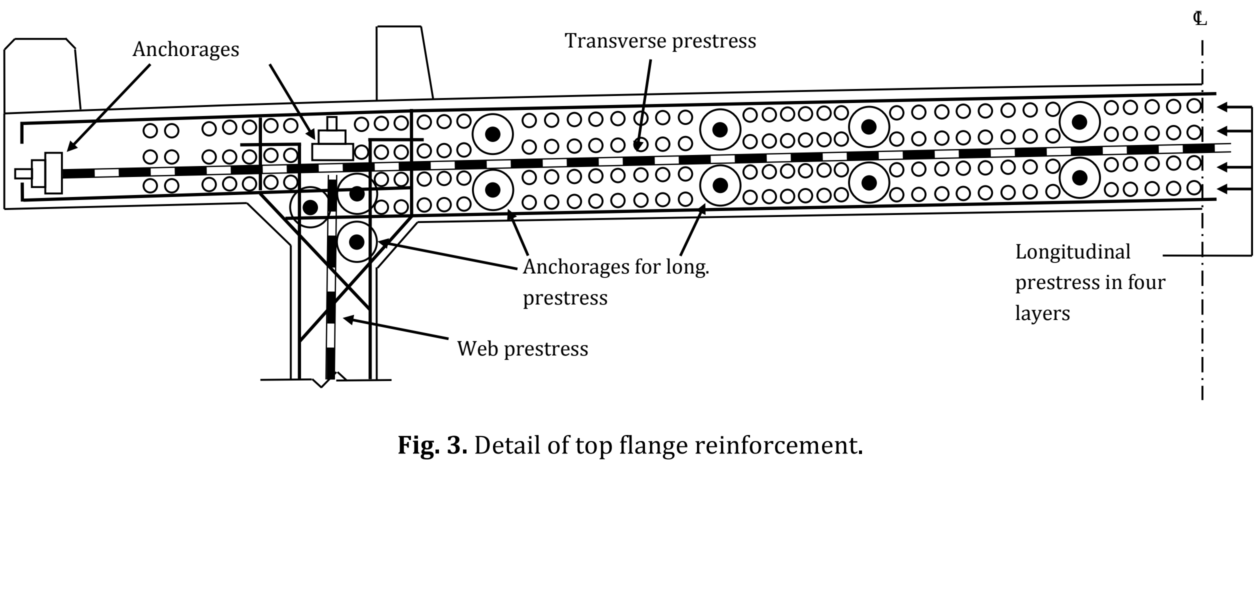


**Fig. 3.** Detail of top flange reinforcement.

The bridge was completed in April 1977, after which it remained unchanged for the next 18 years. On the period the cantilevers deflected due to creep, shrinkage and prestress loss. By 1990 the sag of the centre line, is shown in Fig. 4, had reached 1.2 m (Klein, 2007) affecting the appearance of the bridge causing discomfort to road users, and damage to the wearing surface.

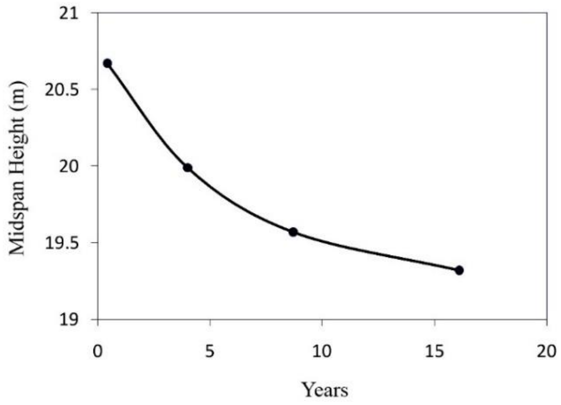


**Fig. 4.** Measured long-term deflection at midspan.

The detailed geometry of one half of the structure is shown in Fig. 5. The $x$-coordinate used here is measured from the extreme back of bridge, with rear support at $x$=18.6 m, and the main support at 72.25 m. This leaves a cantilever of 120.4 m. Variation of centroid location is also shown as dashed curve.

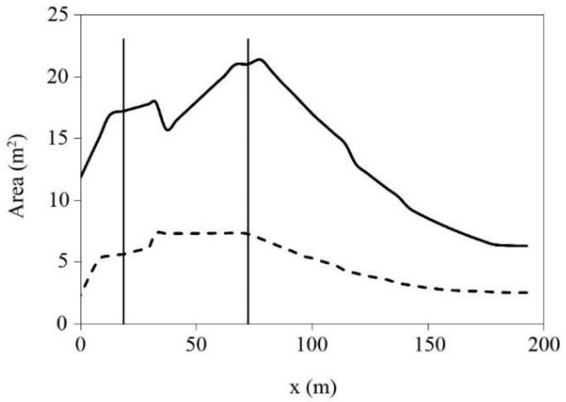


**Fig. 5.** Cross-sections along the bridge.

Variation of moment of inertia of the bridge was given in Fig. 6. In this figure average moment of inertia $I$=160 m$^4$ was given as dashed line.

## 4. Cantilever Bridge

Fig. 7 shows that the as-built bending moment and shear force diagram due to the bridge's self-weight for one cantilever as a solid line. The plotted values included the effect of the ballast in the back span and weight of pavement since these are permanent load. The peak moment at the main support is 1893 MNm while at $x$=84.8 m the moment is 1418 MNm (Fig. 7(a)) and the shear force 32.0 MN (Fig. 7(b)).

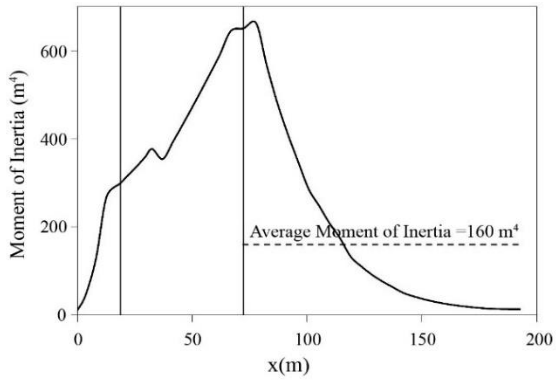


**Fig. 6.** Moment of inertia of the bridge.

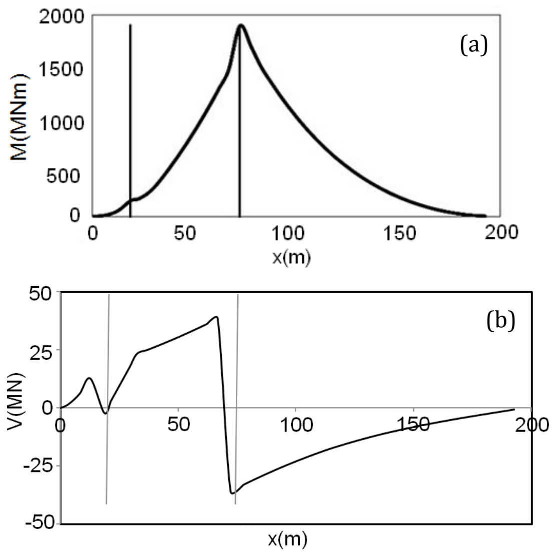


**Fig. 7.** Under the dead weight including ballast and pavement, a) bending moment, b) shear force diagram.

Box girders have been analyzed according to the classical engineering theory of bending in which the cross sections are assumed to remain plane. In Fig. 8, ANSYS finite element modeling is shown. In this simulation of bridge with ANSYS using 5392 hexahedral three-dimensional (3D) finite element with 9614 nodes were used. For threaded bars, 1014 line element by using node numbers in each 45 segments were used. In this section regular reinforcement ratio of the reinforced concrete was chosen as $\rho$=0.003.

As part of the assessment of the bridge a loaded truck weighting 125 kN was driven on the tip of each cantilever to determine its stiffness. Displacement at the tip of cantilever under the self-weight, pavement weight including ballast and prestress was give 127.83 mm, own weight, pavement, ballast, prestress under truck loading give 157.43 mm. Difference between these two displacements 29.6 mm is close enough to 30.5 mm, which is given in McDonald et al. (2004). In this case concrete model is close enough to real concrete used at Palau Bridge in vertical deflection.

KB bridge was collapsed under shear force at $x$=7.08 m far from the main pier face. For this reason stress distribution at $x$=7.08 m was important for this analysis. In Fig. 9 the distribution of shear stress in a cross section located at 7.08 m away from main pier face, is shown when only self-weight or only prestress is considered. It can be seen that a significant shear stress exists in the top and bottom slabs near main pier.

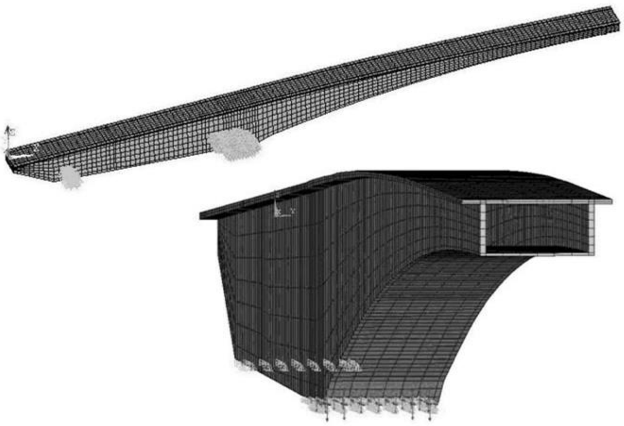

**Fig. 8.** Finite element mesh generation and boundary conditions of the model.

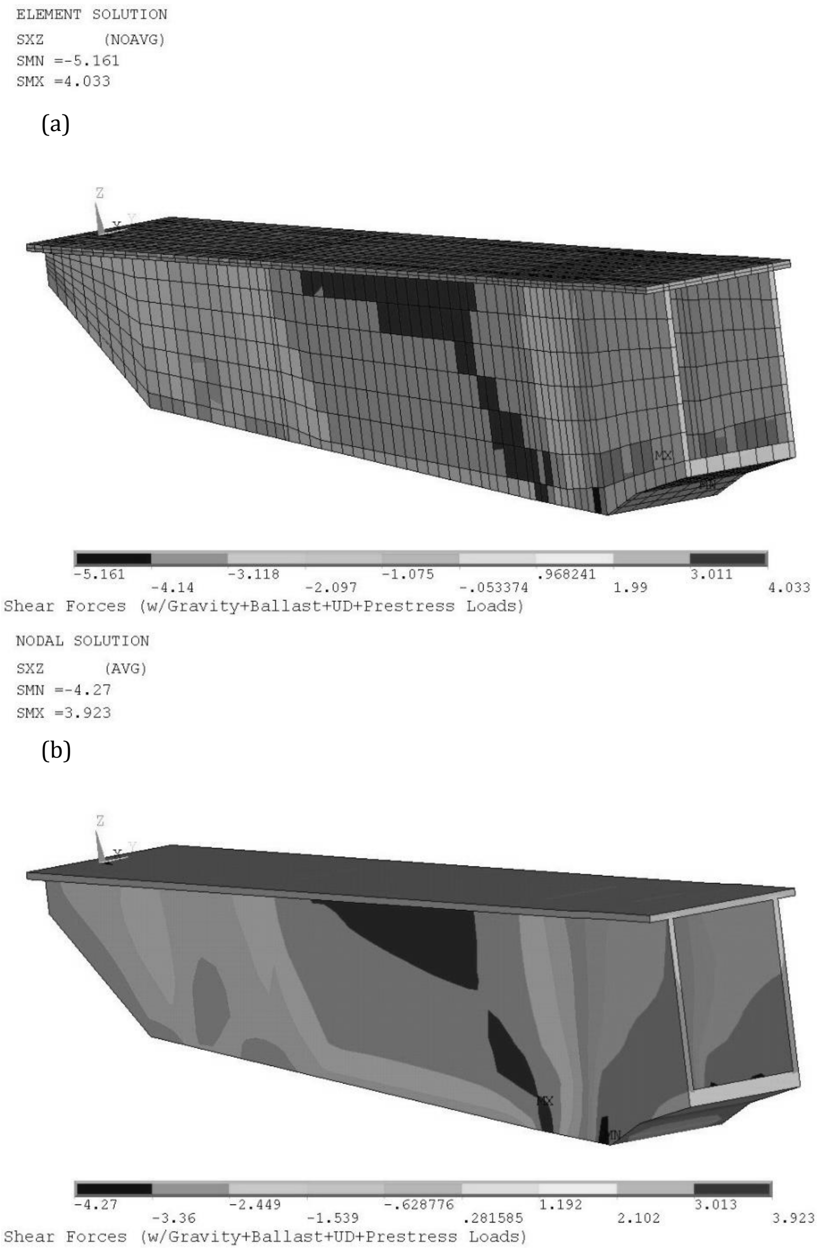


**Fig. 9.** Shear stress distribution at $x$=7.08 m under self-weight and prestress, a) element solution, b) nodal solution.

The total deflection is sensitive because it represents a small difference of two large numbers corresponding to self-weight and to prestress. The shear force plays a more important role in downward deflection by self-weight than upward deflection by prestress. Therefore the neglect of shear may lead to a considerable underestimation of the long-term deflection.

## 5. Repairing

At the results of unexpected deflection at midspan, the government of Palau is decided to take bridge repairing program. The continuity cables pass along the full length of the structure, which had been made continuous. They make contact with the concrete only at the anchorages and at the deflector beams. U.S. company made truck tests at midspan to measure the stiffness of the bridge. Under the 250kN truck loading, they measured the vertical displacement as a $\delta$=30.5 mm. Vertical displacement at the bridge midspan, under the truck loading at the cantilever end, could be obtained from Eq. (1) as well.

$$\delta = PL^3/3EI \tag{1}$$

where, $\delta$=vertical displacement, $P$=concentrated truck loading, $L$=length of cantilever, $EI$=stiffness of box section bridge. By using the measured displacement $\delta$=0.0305 m under the truck loading ($P$=250 kN), in Eq. (1), $EI=250\times120.4^3/(3\times0.0305)=4.76\times10^3$ Nm$^2$ will be obtained. By the help of stiffness and $I$ value from the Fig. 6, elasticity modulus of concrete was found as, $E=4.76\times10^3/160=29.8$ GPa.

During the repairing process, for lifting of bridge at center, help of additional prestressing bars applied 36 MN force. Assume the lever arm of prestressing bars as a 3 m, taking $M=36\times3=108$ MNm, and using Eq. (2),

$$\delta = ML^2/2EI\ , \tag{2}$$

displacement at the cantilever end under the $M$, $\delta=108\times10^6\times120.4^2/(2\times4.76\times10^{12})=0.16$ m was obtained. The vertical and horizontal component of forces exerted by the cable, which is shown with dashed line on the bridge, is given in Fig. 10. Required $M$ for the total displacement $\delta$=1.61 m, was found by using Eq. (1) as $M=1.61\times2\times29.8\times10^3\times160/120.4^2=1059$ MNm. To prevent the prestress loss in bars which already build in the cross section, 20% is enough for displacement, and taking the lever arm 2 m, cantilever end moment $M=0.2\times182.4\times2=73$ MNm was obtained. By this way, $\delta=73\times1.61/1059=0.11$ m vertical displacement, will be eliminated.

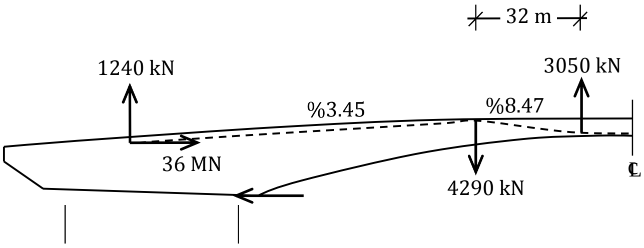


**Fig. 10.** Forces induced by continuity cables.

Second work, to get the deformation of bridge at center back, horizontally embedded 8 flat jacks were installed between the two cantilevers which were jacked apart with a force of 31 MN applied at the center of the top flange at shown in Fig. 11. For the jacking force, by using slope of road 6%, and center of gravity at $x$=86 m was 5.9 m, lever arm will be 0.06×70+5.9=10.10 m. Under the $M=3\times10.10=313$ MNm, vertical displacement, $\delta=313\times10^6\times120.4^2/(2\times4.76\times10^{12})=0.48$ m, totally $\delta$=0.64 m will be compensated during the repairing of the bridge.

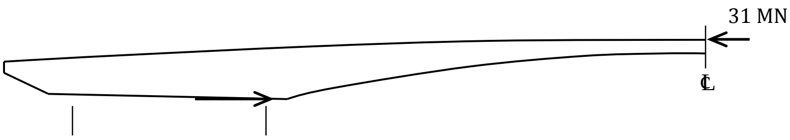


**Fig. 11.** Forces due to flat jacks at center.

Note that there is no force applied to the bridge at the centerline since the tendon does not touch the concrete here. Each side of the main span was prestressed, with a total of 182.4MN of force anchored in the back span between the piers. The other ends of the bars were anchored throughout the main span, at the ends of the 25 segments that made up each cantilever (Fig. 12). In this way a smaller force was applied at the center than at the piers, where a larger moment was experienced. This will be referred to as the original prestress to distinguish it from subsequent additions.

Due to the change in cable profile a prestressing tendon exerts forces on the concrete all along. Its length so the moments in a function of the eccentricity at any position, but the force applied by a jack directly on the concrete retains its line of action throughout the structure. The difference in height between the center of the top flange at the tip, and the centroid at $x$=84.8 m is 10.23 m.

## 6. Discussion

A downward deflection of 30.5 mm was recorded at a midspan when two 125 kN trucks were parked on each side of the midspan hinge. The main goal in this study to compare the results of finite element code based on model Hognestat which give the same deflection as 29.6 mm under the load of 250 kN. The displacement at the midspan of bridge was found close enough to the ANSYS finite element results.

Continuous bridge like as Turkish record holder Beylerderesi and Gülburnu Bridge by symmetric cantilever length is 82.5 m (Çelebi and Harputoğlu, 2006, Harputoğlu et al., 2007), better than the cantilever bridge for the time dependent midspan deflection.

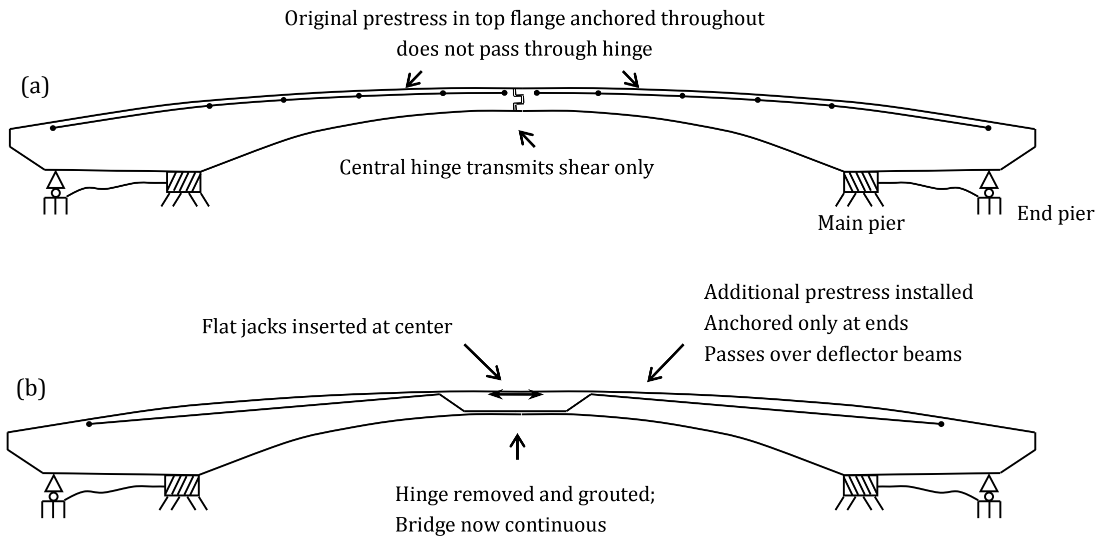


**Fig. 12.** a) Original bridge in April 1977, b) alterations made in July 1996.

## 7. Conclusions

As a result of this study following points were predicted.

- Cross section was always remaining constant during the repairing work, using additional continuity cables and flat jacks increase the amount of reinforcement may cause overreinforced concrete beams.
- Temperature effect is also important in tropical environment. Top face of bridge is always under the sun light with crack around 50°C, but water face is always in compression, no sunlight and temperature around 20°C without crack. This difference increases the drying effect. According to one study (Bazant et al., 1987), weight loss was in the C beam with about 70mm crack length, 2.2 times more than the without cracked C beam.
- The additional complications, caused by changing the structure of bridge from statically determinate cantilevers to a statically indeterminate beam may cause problem. Because cantilever beams are originally cantilevers when the transfer to the continuous beam does not have any continuity bar except additional continuous cables inserted during the retrofit.
- Creep (Bazant, 1972) lead to dangerous deflection and prestress loss should be investigated.

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