Structural assessment of a fire damaged Highway Bridge in Lagos-Nigeria with BRIMOS® Structural Health Monitoring

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ABSTRACT: On the 11th of July in 2008 a fire caused extensive damage to the underside of the superstructure and the piers of the Eko Bridge in Lagos. In several bridge parts the concrete cover at the superstructure's underside failed and the exposed reinforcement bars were partly buckled. Furthermore at several piers concrete has broken off up to a depth of the first reinforcement layers. In those areas where fire caused the most excessive damage, additional temporary supports were erected – surrounding certain piers. In the Site Inspection Report Julius Berger Nigeria PLC stated that without immediate investigations of the structure the safety and stability of the bridges could not be reviewed.
In order to broaden the insight on structural integrity and the load bearing capacity a dynamic bridge monitoring campaign was undertaken. Along with conventional bridge assessment this investigation supports the determination and localization of structural deficiencies.
Particularly evaluation and judgement, to what extent the fire has caused serious damage and tailored recommendations regarding possible retrofit and maintenance interventions were needed to support the decision process of the bridge owner.

1 STRUCTURAL INFORMATION

The Eko Main Bridge East is located in Ijora, Lagos and connects Lagos Mainland with Lagos Island (Figure 1). The prestressed structure consists of two separate load-bearing structures – one for each driving direction. The Main Bridge East which was part of the dynamic investigation has a total length of 190 m and was opened to traffic in the early 1970ies. The cross-section of the superstructures is composed by a three-cellular box girder and has a width of 13.8 m. According to the drawings, a six-span bridge was designed (Figure 2), in fact only five-spans and a cantilever of approx. 5m length in succession to the last bridge bearing were built.

2 SCOPE OF THE ASSESSMENT PROCEDURE

The dynamic measurement at the Bridge object Eko Bridge East with BRIMOS® 11.02 was carried out on the 6^{th} of August in 2010 in order to derive the following key performance indicators:

- The bridge structure's relevant eigenfrequencies and corresponding mode-shapes

- ⇨ Load bearing capacity and operability
- ⇨ Evaluation of the bridge bearings
- ⇨ Distribution of the global and local structural stiffness in the bridge's lengthwise and transversal direction

- Sensitivity analysis to investigate the progression, the character, the stability and probable changes in the energy content of the relevant eigenfrequencies
  - ⇨ Load bearing capacity and operability
- Energy dissipation path in the structure's lengthwise direction
  - ⇨ Dissipation of the induced vibration energy, localization of problematic sections
- Vibration intensity at the entire bridge deck
  - ⇨ Localization of weak points with regard to fatigue threat

Figure 1 : Location of the investigated part of Eko Bridge, Lagos.

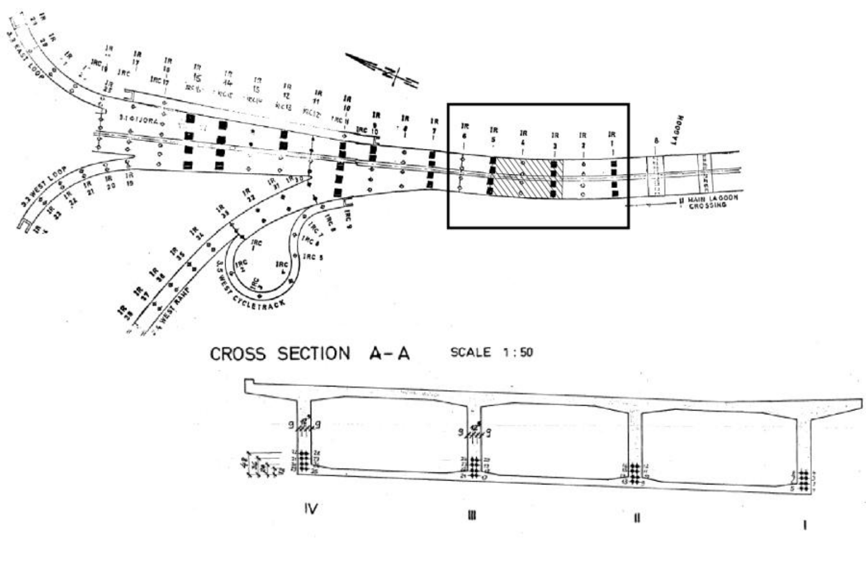

Figure 2 : Plan (top) and cross-section view (bottom) of the investigated part of Eko Bridge.

Parallel to the dynamic measurement an accompanying rapid visual inspection was carried out. As expected, the underside and the piers at the area of span 2, 3 and 4 show severe damage caused by the fire. For further details see Julius Berger Nigeria PLC (2008). The expansion joints are in poor condition due to lack of maintenance. Parts of the railing and almost all manhole covers are missing.

Figure 3 : Visual impression of fire damaged bridge sections.

2.1 Description of the measurement

The measurements were done under ambient conditions on the one hand (environmentally excited vibrations) and under mostly unrestricted traffic on the other hand. The traffic was limited to two lanes including passages of heavy vehicles.

The so-called In-Depth-Monitoring was conducted using two BRIMOS® Recorders with two additional external accelerometers on the one hand and two sets of BRIMOS® wireless units on the other hand. In total a sensor grid of 112 different positions was conducted (Figure 5). On every bridge measurements were taken on the inner (center) and the outer (cap) cantilevers.

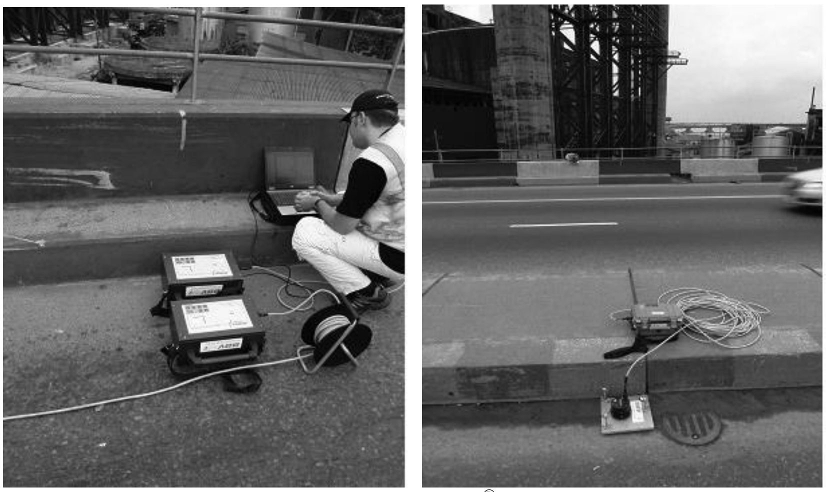

Figure 4: Photodocumentation of the BRIMOS® Measurement at the Eko Bridge.

During the measurements with the BRIMOS® wireless equipment three accelerometers were distributed stepwise all over the structure, while the reference sensor remained at its fixed position. When using the BRIMOS® Recorder and an additional external sensor all sensors were moved stepwise along the measurement grid. In-process referencing enables a coherent analysis of the recorded data.

For each sensor array one measurement file with a length of 11 minutes and a sampling rate of 500 Hz (= 2 milliseconds) was recorded.

Based on the applied dense sensor grid the aerial bridge characteristics regarding bending and torsional behaviour could be observed comprehensively.

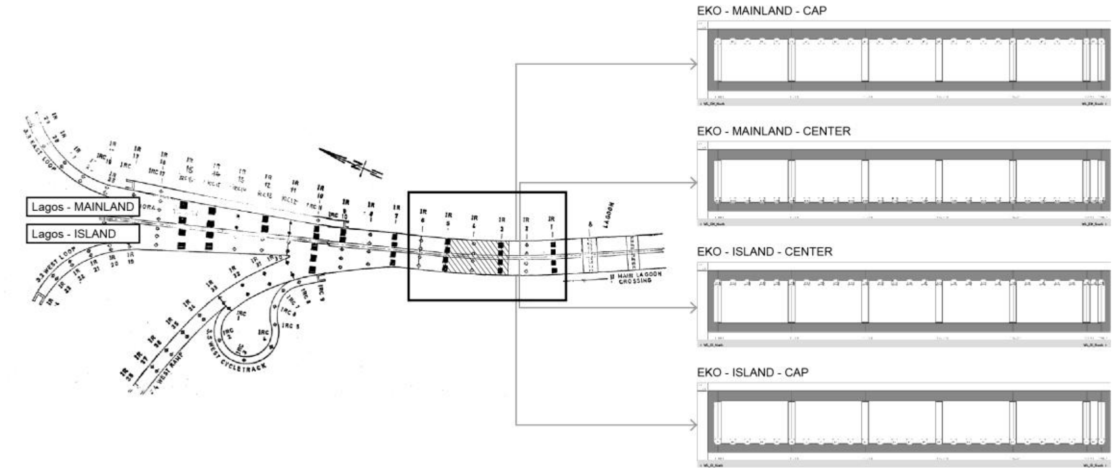

Figure 5: Sensor positions for the 4 applied measurement arrays at the Eko Bridge.

3 DYNAMIC SYSTEM IDENTIFICATION

The following table (Table 1) includes all identified eigenfrequencies which have been considered to be relevant for further evaluation. Some of the corresponding mode shapes are shown in Figure 6 exemplarily. With regard to the nature of dynamic response the origin of resonance is specified respectively.

Table 1: Relevant eigenfrequencies for all measurements.

Eigenfrequencies	Driving Direction Lagos ISLAND			Driving Direction Lagos MAINLAND		
[Hz]	CAP	CENTER	Specification on origin of resonance	CAP	CENTER	Specification on origin of resonance
1. (1st bending mode)	2,92	2,89	span 1	2,91	2,91	span 3 & 2
2. (2nd bending mode)	3,22	3,33	span 4	3,27	3,32	span 1
3. (3rd bending mode)	3,69	3,77	span 1 & 2	3,74	3,76	span 3
4. (4th bending mode)	4,00	3,97	span 4 & 5	4,19	4,14	span 5
5. (5th bending mode)	4,50	-	span 2-5	4,33	-	span 4,3 & 5
6. (6th bending mode)	5,03	-	span 4, 5 & 3	5,26	5,21	span 4,5 & 3
7. (1st torsional mode)	9,20	9,16	span 4, 5 & 3	9,27	8,95	span 4,5 & 3
8. (2nd torsional mode)	-	-	span 1 & 5	12,43	12,47	span 1 & 5
9. (7th bending mode)	-	-	span 4 & 1	12,55	-	span 4 & 1
10. (8th bending mode)	15,11	14,81	span 1 & 2	14,99	14,25	span 1 & 2

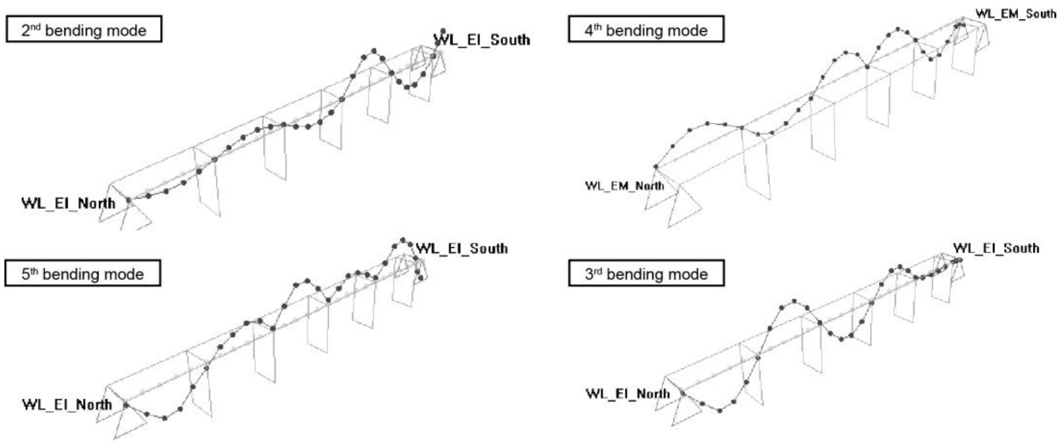

Figure 6 : System Identification – Resonance frequencies vs. type of structural response.

4 ASSESSMENT & EXPERTISE

In the following chapter the key parameters - extracted from structural mechanics (measured vibrational response) are explained with regard to their relevance for civil engineering judgement of the investigated structure. In the forefront – and referring to bridge design – structural load bearing resistance (bending resistance and torsional resistance) are addressed.

4.1 Eigenfrequencies

The frequency spectra in all three analysed dimensions (mainly representing the effective dynamic stiffness of the structure) of the measurements at the driving direction Lagos Island and at the driving direction Lagos Mainland only show a partly distinctive dynamic characteristic. This indicates evident restrictions to the structural integrity of the static system.

The relevant eigenfrequencies are primarily located in the range of 2.5 to 15.5 Hz. Most of those eigenfrequencies are global eigenfrequencies (bending and torsion) linked with dynamic response of whole spans.

Deviations between the eigenfrequencies of the different structures primarily arise from the different geometrical properties (the ground view progression causes varying span lengths - see Figure 2).

4.2 Evaluation of Structural Integrity

So-called trend cards are an essential evaluation instrument for full-scale measurements on bridge structures. They represent the signal either in a frequency-time or a frequency-bridge-length diagram. Figure 7 & 8 demonstrate that the trend cards are obtained by evaluating frequency spectra taken from several measurements, telescoping them together and viewing them from above. For reasons of descriptiveness a two-dimensional visualisation is chosen.

It has to be mentioned that the basic frequencies with their long-wave vibration forms are insensitive to local damage. Therefore the assessment and interpretation of the whole measured frequency spectrum assumes greater significance.

In order to distinguish individual frequency peaks, a colour-scaling of these cards is required - representing the energy content of the oscillation and therefore the respective intensity. From this it follows, that damages are already visible in the frequency spectra in their beginning phase.

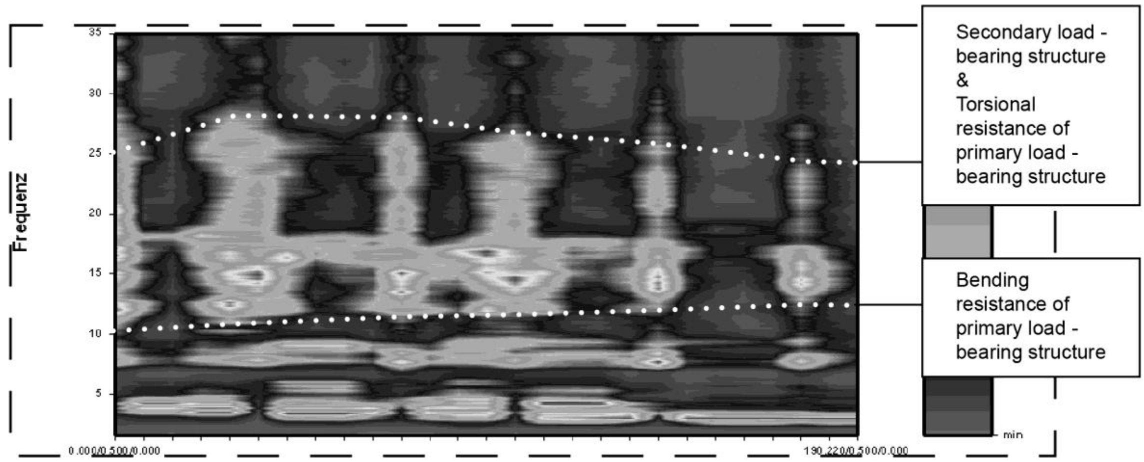

Figure 7 : Distribution of stiffness in the lengthwise direction, 1.5-35 Hz (vert.) - Eko mainland Center

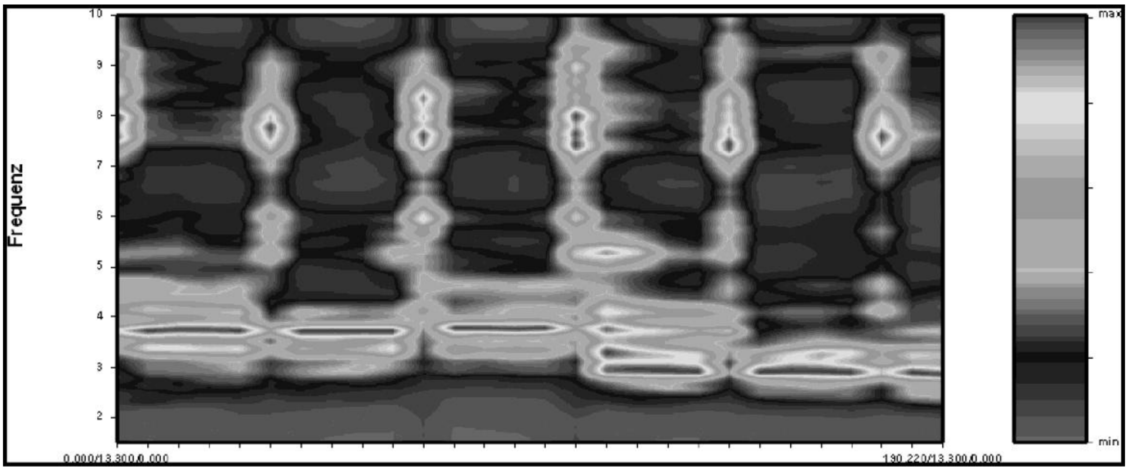

Figure 8 : Distribution of stiffness in the lengthwise direction, 1.5-10 Hz (vert.) - Eko mainland Center

The present investigation aims on an evaluation to what extent the bridge's operability and load-bearing capacity was affected by the fire. For that purpose the trend cards showing the structure's relevant vertical stiffness patterns in the lengthwise direction emerged to be the most suitable instrument. For every measurement two trend-cards were derived. The first one shows the bridge's relevant stiffness patterns in the range of 1.5 to 35 Hz (Figure 7) the second one illustrates the range of 1.5 to 10 Hz in detail (Figure 8).

Due to the bridge's geometry (similar span length and identical cross section) an equal distribution of the structural integrity along the entire bridge length could be expected.

In fact the damage led to an considerably reduced bending resistance of the primary load-bearing structure at the affected regions of span 1, 2 and 3 (Figure 8). The analysed mode shapes confirm the presence of the addressed bending resistance but at the same time the trend cards underline their lack of availability in the course of load bearing activity due to their minor visibility (Figure 7). This causes a redistribution of the internal forces to the higher frequency range leading to an intensified stressing of the torsional resistance of the primary load-bearing structure and the secondary load-bearing structure (Figure 8).

Furthermore trend cards of vital structures usually show a clear separation between pier and span areas (confirming the proper development of designed stiffness-concentrations). While this necessary attribute is visible for the spans 4 & 5, the rest of the bridge (spans 2 & 3) indicate an inefficient force transmission, as the described separation becomes indistinct (Figure 8).

4.3 Mode Shapes

The determined mode shapes are characteristic for this kind of structures and correspond to the expected modes of vibration. Several representative mode shapes for the left and the right structure are presented in Chapter 3 (Dynamic system identification – Figure 6). Although the load-bearing capacity is limited (poor developed frequency spectra) the determined mode shapes indicate that the bridge's operability is available in principle.

4.4 Vibration Intensity

In the present case vibration intensity is analysed and classified according to Beards (1996). The vibration intensity is subdivided into 4 zones, ranging from low probability of damage (Zone I) up to very high probability of damage due to dynamic stress (Zone IV).

The Eko Bridge responds sensitive to traffic impact loading, showing values of vibration intensity in the range of zone I and II but also already at the boarder to zone III.

Under operational conditions range II indicates a level of impact, where damage might be caused by continuous dynamic stress. Range III indicates already a level of impact, where permanent dynamic stressing will cause damage to substantial parts of the structure. The high intensities are also triggered by the insufficiently working expansion joints which seem to have no proper operability anymore. A future assessment and observation of the structure regarding fatigue-relevant damages should be performed in periodic time intervals.

4.5 Dissipation of induced vibration

The analysis of the RDT-based damping values (according to the applied sensor grid) provides a suitable indication for the condition of a structure and the main girders respectively. "Problematic zones" mostly dissipate energy by means of friction which is reflected in an increase of the local damping values. Higher damping values in the area of abutments or piers are a logical consequence of the static system. Thus they have no direct influence on the assessment of the structure's condition.

The given results confirm the operability of the bridge in principle. Parts of those areas where the bridge was damaged by the fire impact clearly show increased damping values indicating reduced bending and torsional resistance.

Apart from that the pattern of RDT-damping values in the lengthwise direction of all measurements is typical for such a structural type and primarily reflects the dominantly occurring system damping due to the mechanical behaviour of the bridge.

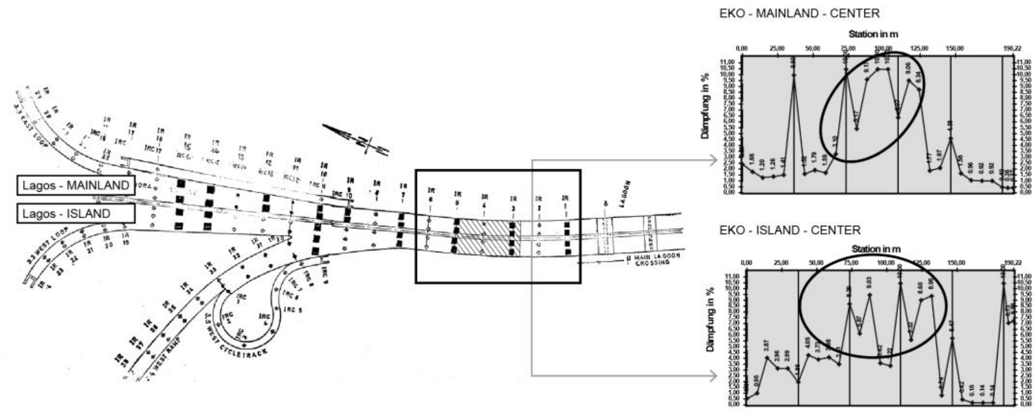

Figure 9 : Overview – Exemplary RDT-Damping patterns - confirming heavy damage.

5 SUMMARY & RECOMMENDATIONS

5.1 Summary

The present in-situ measurements indicate that the structure's load-bearing capacity is not available to its full extent. The analysis of the measurements shows heavy damages of the superstructure. The bottom layer of the internal prestressing was affected by the fire.
The operability is still given in principle at the time of investigation.

According to the performed measurements no immediate action concerning rehabilitation measures but certain short term and mid-term action addressing the bridge deck, the bridge bearings and the piers are required. The need of strengthening three spans with external prestressing is stated.

The dynamic measurements revealed that there is an evident reduction of structural resistance of the primary load bearing structure, mainly affecting bending stiffness. The bridge's redundancy enables a redistribution of the occurring internal forces under operational conditions into the higher frequency range.

5.2 Structural Measures & Recommendations

Short-term actions:

- Removal of waste and sand from the box-girder to reduce the dead load.

Mid-term actions:

- The delaminated concrete at the bridge deck's bottom side should be removed with high pressure water blasting.
- The damaged reinforcement and concrete cover has to be replaced.
- A strengthening of the spans 2, 3 and 4 by external prestressing is recommended.
- Damaged bearings are to be replaced. A proper replacement concept is to be elaborated and implemented, which could be combined with a replacement/retrofit program of the damaged piers.
- The damaged expansions joints intensify the force transmission into the structure and contribute to the high vibration intensity. Therefore a replacement of all damaged expansion joints is recommended.
- A static recalculation addressing the bridges post-tensioning is recommended - considering the failure of the lower tendon layer caused by fire.

According to the BRIMOS® classification the structure is rated as category C. This category represents „structures in problematic condition“. After the extensive investigations a moderate threat of bridge collapse has to be stated.
This rating is based on measured and evaluated dynamic parameters (Key Performance Indicators), an accompanying visual inspection and reference data from the BRIMOS® Database. The experience of about 1000 investigated structures worldwide has been incorporated into the assessment procedure.

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