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APPLICATION OF TIME SERIES ANALYSIS FOR BRIDGE MONITORING

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This paper describes a methodology to study the structural behavior of a bridge superstructure based on recorded time histories of strains at selected cross sections. Vibrating wires (sensors) were installed along the length of the superstructure in order to measure strains in different directions. The locations of the sensors were selected based on the results of numerical analyses. Additional sensors were placed on the top flanges of transition segments (orthotropic to composite) in order to measure the possibility of sliding/separation of the top steel flange and the concrete slab. Furthermore, on each side of the bridge, three tilt meters measure rotations whose magnitudes are used to calculate displacements in the vertical direction.

The problem to convert large amounts of data into usable information is addressed. The technique adopted is based on a time series analysis. As a first approach, a visual inspection of time histories of strain data is performed in order to identify possible problems in the data. For the study of long and large time histories of strain data, ARIMA (Autoregressive Integrated Moving Average) model and other statistical techniques are used to study the structural behavior of the bridge at three different cross sections. Finally with the use of statistical data and a process of statistical control, a method to evaluate the health of the bridge is proposed. The data used in this paper were recorded by a SHM system two years after the bridge was open to traffic in May 2006. Results are processed statistically and probability distributions are derived.

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ABSTRACT: This paper describes the in-progress monitoring and preliminary structural evaluation based on recorded time histories of strains at different sections of a special bridge with a very difficult geometric alignment. Vibrating wires were installed along different segments of the superstructure in order to measure strains in different directions. Locations for these sensors were selected based on the results of numerical analyses. The problem to convert large amounts of data into usable information is addressed. The technique adopted is based on a time series analysis. As a first approach, a visual inspection of time histories of strain data is performed in order to identify possible problems in the data. For the study of long and large time histories of strain data, ARIMA (Autoregressive Integrated Moving Average) model and other statistical techniques are used to study the structural behavior of the bridge at three different sections. Finally with the use of statistical data and a process of statistical control, a method to evaluate the health of the bridge is proposed. The data used in this paper were recorded by a SHM system two years after the bridge was open to traffic in May 2006. Results are statistically processed and probability distributions are derived.

1 INTRODUCTION

In recent years Structural Health Monitoring (SHM) systems have become important in many engineering applications. In the case of civil structural monitoring, bridges are one of the most common monitored structures with SHM systems. In many cases SHM systems are working continuously and produce large amounts of data from which information must be extracted to obtain knowledge about structural conditions of the bridge. This paper shows the application of time series concepts and statistical analysis to the information recorded by a SHM system installed on the superstructure of a curve bridge. The analysis deals with the information obtained during two years by means of a set of sensors distributed along the total length of the superstructure. The analysis is based on ARIMA (Autoregressive Integrated Moving Average) models to record increments of stresses. Afterwards, with the application of a methodology known as Box Jenkins and the use of techniques of statistical control, parameters derived with ARIMA models are used to define statistical control charts, whose purpose is to define a simple way of reducing and managing a large volume of data.

2 DESCRIPTION OF THE BRIDGE

The bridge is located in a horizontal curve with transverse and longitudinal slopes of 10 and 5%, respectively. The superstructure consists of a continuous Grade 50 steel

orthotropic and composite box of constant height (5 m) comprising 3 spans (72.53 m, 177.94 m, 72.53 m) , with a total length of 324 m. The top deck is 13.64 m wide incorporating two traffic lanes. A top postensioned concrete slab of 0.30m is used in the composite section; shear studs provide the interface between the top flanges of the open box girder and the concrete slab. The superstructure is divided into three parts: two lateral parts of 111.63 m long with the composite section and an intermediate part of 100.74 m long with the orthotropic section. The substructure is composed of two conventional reinforced concrete abutments and two piers of rectangular hollow cross section of about 61 m high each. The maximum depth, measured from the bottom of the superstructure to the bottom of the ravine, is about 200m. Elevation and plan views of the bridge are shown in Figures 1 and 2, respectively.

3 INSTRUMENTATION

Instrumentation was designed and implemented to monitor stresses, displacements, deflections and temperature along the bridge. For its implementation the superstructure was divided into two halves: Tuxtla and San Cristobal sides. Each half consisted of 14 segments, denoted by D. Segments were identified according to Figure 2.

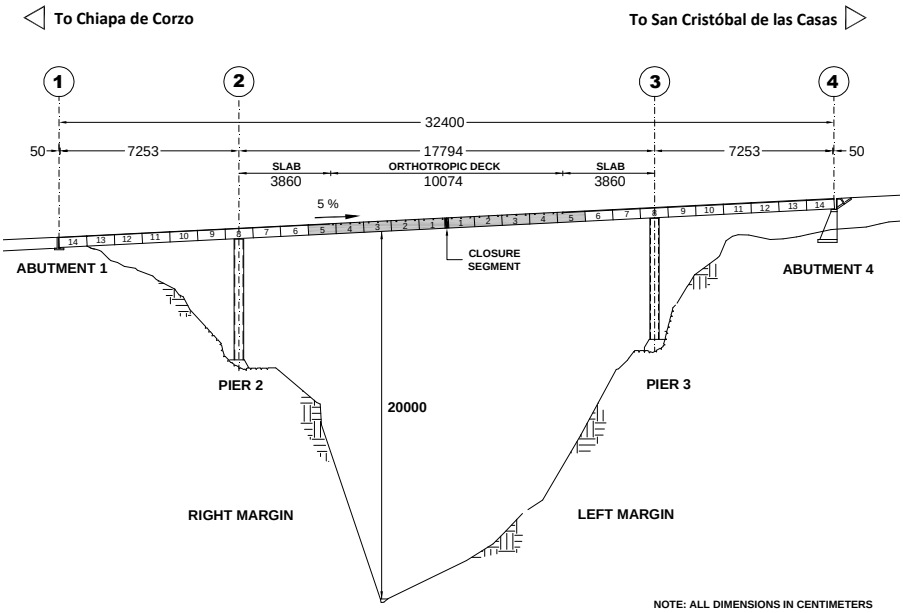

Figure 1. Elevation view of San Cristóbal Bridge.

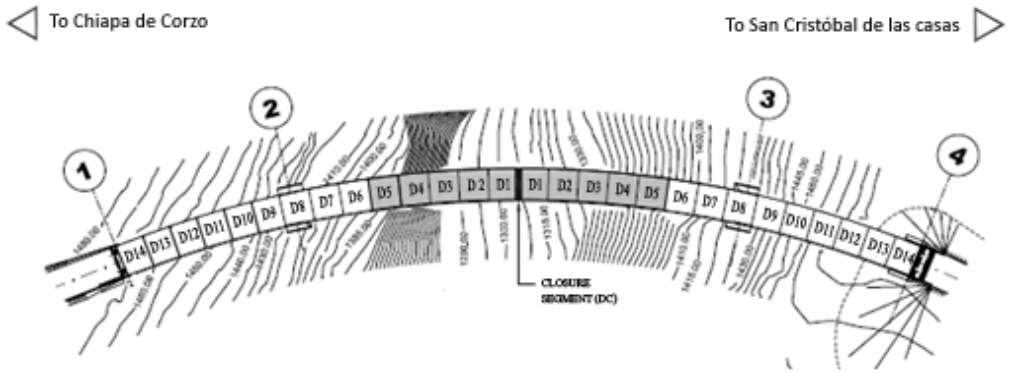

Figure 2. Plan view of San Cristóbal Bridge and identification of segments.

The instrumentation consists of: a) 102 vibrating wires distributed along the bridge superstructure, oriented in the longitudinal direction L (parallel to the curvature of the bridge); these sensors also recorded temperatures; b) 6 inclinometers oriented in the direction L and T (normal to the curvature of the bridge) along the central span of the superstructure; and c) 36 resistance strain gauges distributed over the bridge superstructure, oriented in the longitudinal direction L, Gómez (2009). The distribution of the instrumentation was as follows: vibrating wires segments were placed in segments D11, D8, D4 on both sides of the structure, and in the central segment DC. In order to measure the relative displacements in the zone of transition (change of orthotropic floor to concrete slab) vibrating wires were placed in the top of segment D6 on both sides. Bidirectional inclinometers were placed on the tops of the segments D1, D6 and D8 of both sides of the bridge, with the purpose of recording rotations around the directions T and L. Figure 3 shows cross sections of the instrumented segments.

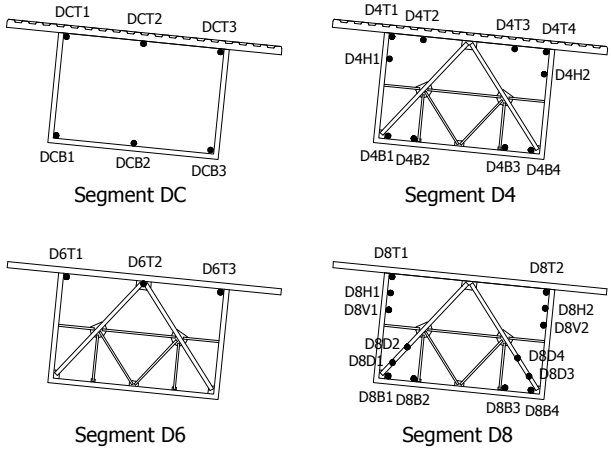

Figure3. Location of vibrating wire sensors in different cross sections of the bridge.

4 INFORMATION RECORDED

Because of the large number of sensors and consequently a large volume of data, this paper focuses specifically on the information produced in the vibrating wires. The structural parameter under study is the increment of strain recorded at three different sections fo the bridge: segments D4 on both sides of the bridge and segment DC (see Figure 2) . In the specific period of the study (November 5, 2006 until January 2, 2009), vibrating wires generated 102 records. Application in recent years of ARIMA models,

for modeling and forecasting a large number of physical phenomena in the field of civil engineering (particularly in Structural Health Monitoring, SHM), has brought many advances and achievements related to the modeling of phenomena and forecast of future scenarios, Wei (1993). At present time it is still challenging to predict the evidence of damage, its magnitude and location through the analysis of structural parameters, as the increment of strain ($\Delta\varepsilon$) or stress ($\Delta\sigma$). Up to now theoretical applications have only been able to model and provide forecasts, however, there are some starting points indicating that it is possible to determine whether changes in measurements are really important and could be associated to deterioration or damage in a structural system. In order to analyze the information recorded in a time series approach and in particular under an ARIMA modeling, recorded measurements at the bridge were separated from 8:00am on April 1, 2007 to January 2, 2009. Since the Box-Jenkins methodology, Hanke and Wickery (2006) applies only to time series with discrete time intervals, recorded time series were equally spaced: every 24 hours. The same was applied to data pertaining to 8:00pm on April 1, 2007 to January2, 2009. The resulting time series have a total of 728 data. Later strain increments plotted the 102 captured by vibrating wires. Figure 4 shows an example of the time series data of segment D4 recorded at 8 am (April 2007). Due to some flaws in the recording devices, the associated records were corrected by visual inspection.

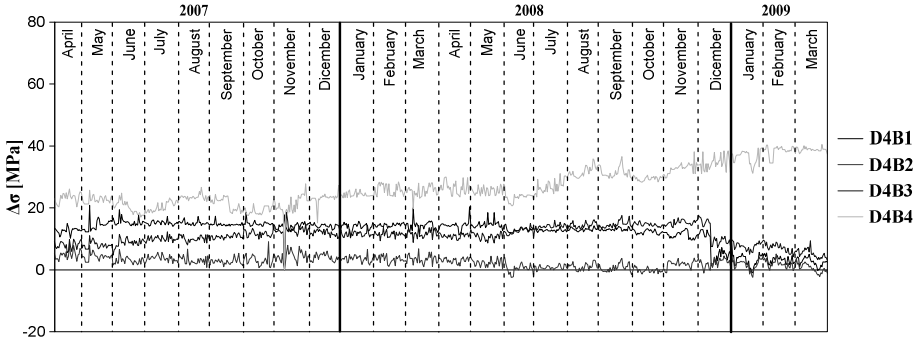

Figure 4. Example of recorded stress increments in segment D4, bottom plate, Tuxtla Gutiérrez side (8:00AM).

5 ARIMA MODEL FITTING

This section presents the process applied to information pertaining to sensors placed at three different cross sections (D4, Chiapa de Corzo side; DC; and D4, San Cristóbal side). The bottom plate of segment D4B4 is taken as example. The time series are subjected to classical linear regression analysis with two specific purposes: to observe trends in the series and to identify seasonality and its corresponding period. Results of this analysis showed that the series had a trend and no seasonal component. Afterwards, stationary was induced and some ARIMA models were identified. After several trials, it was finally decided that an ARIMA model with parameters ($p = 0$, $d = 1$and $q = 1$), i.e. ARIMA (0,1,1) would provide sufficient accuracy. Figure 5 shows a comparison of an actual time series and the one estimated with ARIMA model. It must be mentioned that several ARIMA models could be adjusted properly to the series. In this specific case, ARIMA (0,1,3), ARIMA (1,1,1), ARIMA (5,1,0) and ARIMA (3,1,4) models were also

processed, Cortés (2011). Only 628 points out of 728 were considered. The missing 100 points were used afterwards for prediction purposes, as it is regularly carried out when using the Box-Jenkins methodology, Box &Jenkins (1994). As mentioned, 100 predictions were generated based on the fitted ARIMA models. This is equivalent to obtain the increments of strains/stresses for 100 days after the last date of analysis. Figure 6 shows the prediction obtained with ARIMA (0,1,1) model using only 628 observations of stress increments with a confidence interval of 95%, as well as the measured values. It is observed that actual values are in the confidence interval and predicted values converge to a straight line with constant slope in a long run, which means that ARIMA models are only valid for short term periods. In spite of the observed trend, it is important to establish a starting point to determine whether changes in recorded time series, obtained by means of SHM systems, are really important and could be associated to damage or deterioration of a structural system. The use of ARIMA models to develop a tool for monitoring the described bridge will be presented in the following paragraphs.

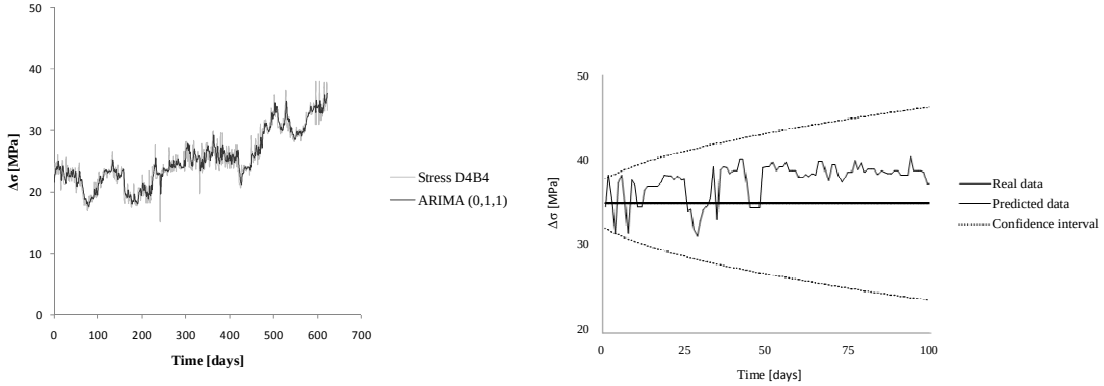

Figure 5. To left, coparison of D4B4 time series and ARIMA (0,1,1) model. To rigth, predicted data with ARIMA(0,1,1).

5.1 Statistical Process Control (SPC)

The assumptions of the SPC are described in the following lines. The current records (acceleration, stress, strain, etc.) represent the healthy state of the structure. Records are generated by an unknown process represented by a given ARIMA model. A change in the structural properties of the system will undoubtedly be reflected in the records, which means that the deterioration process consequently change the coefficients of the model. Not every change is significant or relevant. The old coefficients have some variability, but still represent the same process. If new records show a significant change in the ARIMA model coefficients, this can mean deterioration and / or damage to the structural system. It is worth to mention that the use of this tool in this work is limited to establishing the initial conditions, considered the healthy state of the bridge superstructure. Likewise, because the structure under study was recently built and therefore is considered healthy, the objective of this study was not to analyze the extent of possible damage and identify it. Consequently there is no record of any possible deterioration of the structure state. Records as of March 2009 are available. In order to set limits of allowable or optimum reference, Everett & Ronald (1992), an statistical control process was used as a tool in the monitoring of the structural health. New and old records are compared by means of a control panel to identify inconsistencies

between them. The control chart is built from information generated at the start of the useful life of the structure, which is associated to the state zero or initial state of the structure, commonly referred as the healthy state. The theory of the process of statistical control, specifically in the construction of control charts, requires no correlated data. That is why in this paper the use of residuals of the ARIMA model, adjusted to the observations, is proposed, because records are independent from each other, this is, there is no correlation between them. It is also proposed the adjustment of a purely autoregressive model (AR), because of the ease to handle this type of models. To apply ARIMA models and an statistical control process to the structural monitoring, the following procedure must be followed, Fugate, Sohn, and Farrar (2001): An AR model of order p is fitted to the information in the initial state of the structure (healthy). If the condition of the structure has not changed, then it should be expected that the new residuals are mostly within the top and bottom limits. If a significant change has taken place in the structure, it is expected that a high percentage of residuals will be beyond the control limits

5.2 Construction of the graph of sample mean

In the following, the construction of the control graph X corresponding to the increments of strains associated to B4D4, from April 1, 2007 to December 18, 2008 is presented. In addition, the ARIMA model (5,1,0) is adjusted to series whose coefficients are φ_1=-0.6024, φ_2=-0.-0.3129, φ_3=-0.2151, φ_4=-0.1958 and φ_5=-0.1102. To begin construction of the graph, we will use the adjustment of the ARIMA model to 628 observations. As a result of the differentiation in the series and the adjustment a total of 622 residuals were obtained. The mean and standard deviation values are: μ=0.53, σ=15.00. With these values, residuals are normalized by means of the following equation:

$$\hat{a}_{t),N}$$

where:

$\hat{a}_{tN}$: normalized residual

The new mean (μ) and standard deviation (σ) have the values of 0 and 1, respectively. Afterwards, by means of a normal standard distribution the limits of statistical control denoted as UCL (Upper Control Limit), LCL (Lower Control Limit) and Cl (xx), are obtained. For the point of interest, D4B4, the obtained values were CL=0; UCL=0+3(1)=3; and LCL=0-3(1)=-3. The control chart is constructed as presented in figure 7. Finally, the normalized residuals are plotted:

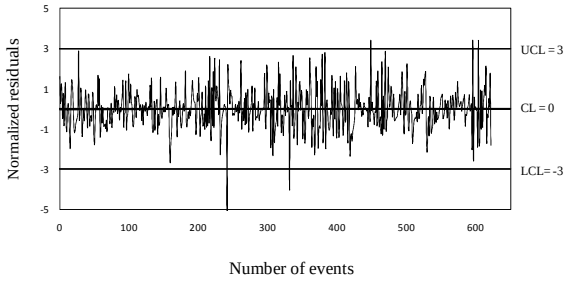

Figure 7. Normalized residuals, segment B4D4 on $\bar{X}$–bar control chart.

It is observed that most of the standardized residuals of the ARIMA model are within the limits of control. Only 5 measurements out of 628 fall outside these limits, which is no indication that there is a significant change in the parameter studied (increment of stress). In order to avoid false warnings (signs of significant changes in the structural parameter when in fact had not been submitted), the validity of the table is verified with data from December 19, 2008 to March 28, 2009. This are the last 100 captured data, and they are used because with certainty they are representative of the healthy state of the structure, as well as the data used for the construction of the control panel. Therefore, when providing this new information to the control panel, it is expected that there will not be a large number of data beyond the limits of control. Through this test, the effectiveness of the control panels in the structural monitoring is examined. The procedure is as follows: The new information is adjusted to the same ARIMA model, established at the beginning: ARIMA (5,1,0) with the same computed φ_i coefficients. This adjustment provides a total of 94 residuals which are normalized using the mean and standard deviation obtained for the first time series: μ=0.53, σ=15.00. They are plotted in the same control panel presented in Figure 8. It is observed that the new residuals are within the limits of control. Only 2 measurements out of 94 fall outside these limits, which is no indication that there is a significant change in the structural parameter. It is verified that the control graph does not emit false alarms, because both series, in the healthy state of the structure, are within the allowable limits. It may be inferred that the panel is reliable and an be utilized for structural monitoring.

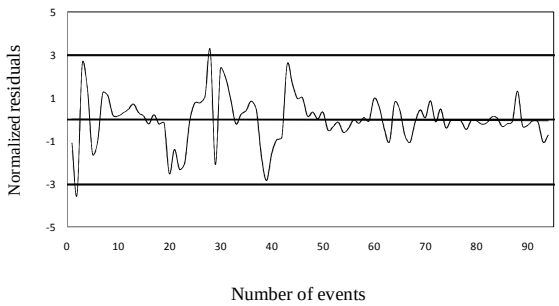

Figure 8. Residuals of the adjustment of model ARIMA(5,1,0), 100 data in the control graph $\bar{X}$.

The described process was applied to all points at the three cross sections described. In all cases results indicated a good fit of the ARIMA model used at each point and a

control statistical graph with few points outside the boundaries of control. Figure 9 shows the results obtained with the ARIMA models and the control graphs for a specific point of each of the three cross sections analyzed.

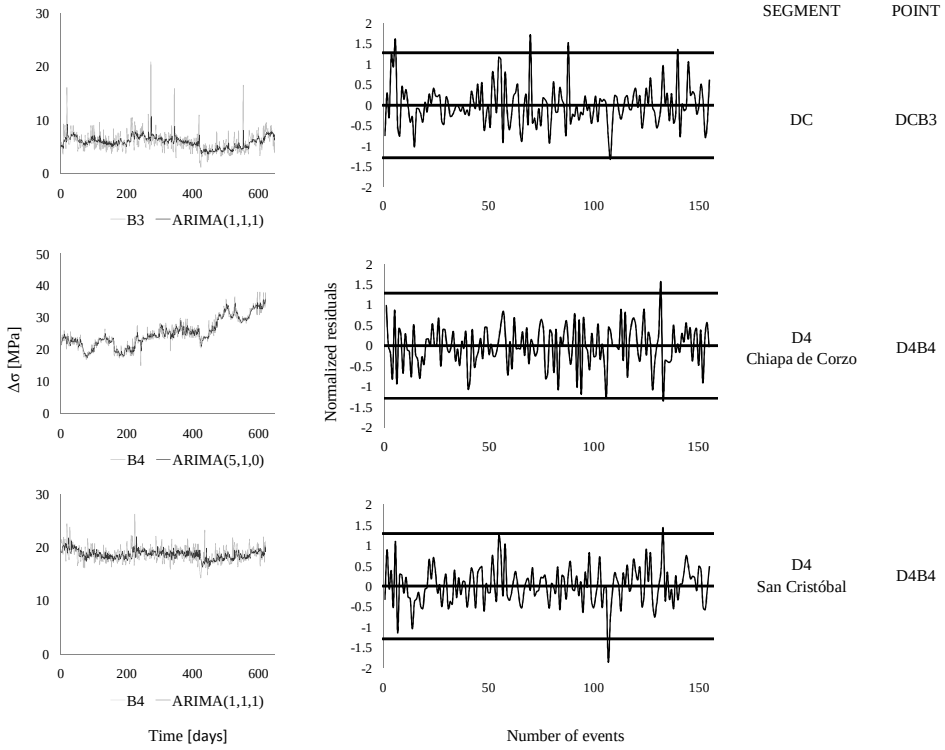

Figure 9. ARIMA models and control graph $\bar{X}$ obtained at recording points of segments D4 and segment DC.

6 CONCLUSIONS

ARIMA models provide a unique fitting for any time series. The fittings to the series under study increase in stresses in all the studied segments are very good. The degree of adjustment of the models has not been reached with a classical analysis, in which the only detectable and patterned component was the trend. However, even there are improvements that can be made in the methodology, especially concerning the identification of the seasonality in the series. Results of this analysis showed that the series had a trend and no seasonal component. Statistical control of processes through the control graph is a simple and viable option for the quick monitoring of the conditions of a structure. Once the graph is built, new information can be analyzed in a short period of time. On the other hand, the classifier algorithm complements the process of statistical control, because it separates in classes the different conditions of a structure. Future works should focus on the automation of both tools and in the definition of reasonable limits on the changes which will undoubtedly occur in the San Cristóbal bridge. From these limits, preventive measures that will ensure the security conditions in this type of infrastructure may be established. Finally, it is worth noting that the limits UCL and LCL may be somewhat rigorous considering that currently the acting stresses of the bridge are approximately 40% of the allowable value. For this reason, it might be useful to establish less conservative control limits that take into

account the inevitable increase in acting stresses on the structure due to the fatigue of the material and the wear of the structure, and of course, these must not exceed the allowable stress. Although the information used in this paper only corresponds to a specific period of monitoring, the established methodology can be extended to records of greater extension registered at any time. This will improve the methodology and will profit from the existing information.

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