Int J Interact Des Manuf (2018) 12:253–261
https://doi.org/10.1007/s12008-016-0361-0

TECHNICAL PAPER

Full scale fatigue test performed to the bolster beam of a railway vehicle

R. E. Gutiérrez-Carvajal[1] · German R. Betancur[1] · J. Barbosa[1] · Leonel F. Castañeda[1] · G. Zając[2]

Received: 29 September 2016 / Accepted: 3 November 2016 / Published online: 22 November 2016

Abstract Many structural elements are exposed to conditions of load that are difficult to consider during the design stage, such as environment uncertainties, random impacts, overloads and inherent material idealization amongst others, hence, miss-estimating its life-time cycle. One way to test those designs is to construct a representative full-scale specimen and test it under the most critical load conditions in a controlled laboratory. Herein, we present a case of study of the fatigue test performed over a bolster beam redesigned in Universidad EAFIT belonging to a railway vehicle. The test was composed by three stages, each one testing a different load hypothesis. The bolster beam was instrumented at the most critical locations, following the results of a FEM analysis previously computed. As results, the most critical welds were identified and the total damage computed for an equivalent operation of eighteen-years, and also the behaviour of the specimen in presence of extreme longitudinal loads.

This work was partially funding by the "Patrimonio autónomo Fondo Nacional de Financiamiento para la Ciencia, la Tecnología y la Innovación, Francisco José de Caldas".

✉ R. E. Gutiérrez-Carvajal
rgutier7@eafit.edu.co

German R. Betancur
gbetanc4@eafit.edu.co

J. Barbosa
jbarbosa@eafit.edu.co

Leonel F. Castañeda
lcasta@eafit.edu.co

G. Zając
grzegorz.zajac@mech.pk.edu.pl

1 GEMI research group, Universidad EAFIT, Carrera 49 N° 7 Sur-50, Medellín, Colombia

2 Instytut Pojazdów Szynowych M8 Politechnika Krakowska, Kraków, Poland

Keywords Fatigue test laboratory · Full-scale fatigue test · Railway vehicle component · Structural damage · Strain signal analysis

1 Introduction

Modern manufacturing requires to produce reliable goods in short time [21]. It is usually performed following almost five steps: problem description, a non intrusive analysis, modeling, interactive simulation and simulating the product using a virtual model [13]. However, computer models impose suppositions that could not fit the real operation. For this reason, it is necessary to include a mechanical test on the product prototype when designing critical components. This tests allows to obtain information about the product life span, useful to analize the product life cycle[23]. In the case in which the product does not behave in the way it was expected, the design must be rejected and tune again the computer models. It could be noted that the success of interactive design and manufacturing is strongly based on the accuracy of the models tested, being the ground truth the physical final product. In this article, we present the fatigue test performed over an prototype of the structural component of a railway vehicle, using same materials and assembly process than expected for the final product. The test was supervised continuously and the stress of the critical points identified and its behavior during it life-span recorded and analyzed.

Although structural test are performed typically over small specimens as it is cheaper than full-scale test, are reproducible at several location yielding similar results and are regulated by ASTM, may of them are oriented to obtain parameters impossible to extract analytically, hence there is naive to extrapolate those parameters to simulate the performance of actual structures [31].

On the other hand, full fatigue test is now a mature technology and considered as a crucial stage in the product evaluation process. It allows to emulate several properties of a product, such as its life span, damage accumulated under certain load cases, it allow to locate probable fissures, analyze the effects of loads over critical weldings and joints, confirm the structural design and calculation amongst others avoiding assumptions different from the case of loads applied [2]. Hence, it has been implemented in several industries, such as, civil industry in redesign of bridges[2], aeronautical industry testing elements and also testing technology for structural health monitoring [20,22,30], testing fatigue effect in weldings [7] and railway industry testing [28], carbodies and other components [18].

Application of full scale fatigue tests is especially relevant at validating critical structure elements relevant for safety of the device. An accurate fatigue test takes into account mixture of loads that affect the structure and are hard to be considered during the design stage. In particular, railway-vehicles are designed to operate at more than twenty-five years [5,14], but real-life conditions present a complex mixture of alternated loads specific for each railway system implementation, such as railway routes, type of vehicles, schedule of operation and maintenance program amongst others. This could result in early wearing of components, namely: wear, cracks and fissures of structural elements; requiring frequent corrective maintenance tasks and also reducing dramatically its lifetime of operation [3,24].

The bolster beam is the main structure of the carbody, and is not a disposable piece in which a failure could be catastrofic [29]. A diagram of the location of the bolster beam in the railway vehicle is shown in Fig. 1. Its is designed to support the bogie yaw, but maintaining enough comfort for passengers [19]. Several authors reported occurrence of cracks after few years of operation [1,29], reappearing after welding them, so requiring posterior analysis of their causes. The diagnosis of a bolster beam consists in a set of nondestructive test, such as magnetic particles, ultrasound, permeable liquids, amongst others, that requires to get out of service the entire train operation, thus decreasing its availability. On the other hand, in presence of fissures, the repair action consist in look for an expert operator to weld the fissure, which level of expertize depends on the location and type of weld [8]. Hence, it is critical to maintenance manager to estimate when and where a fissure will appear. Considering this issues, EAFIT University designed and produced a new bolster beam element [15] to which we performed a destructive fatigue test.

Bearing these ideas in mind, the rest of the article is organized as follows: Sect. 2 explains the experimental setup and methods used; Sect. 3 presents the results obtained with our method, Sect. 4 discusses the main results; and finally Sect. 5 introduces the main conclusions of this study.

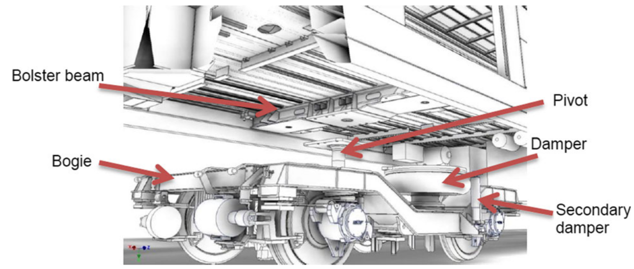

Fig. 1 Railway vehicle components. The bolster beam support loads coming from the carbody and also from the bogie through the pivot as interface element

Table 1 Relation of the case of load tested at each stage

Stage	Load case				
	P	R	Q	S	T
Stage 1	X	X			
Stage 2			X	X	
Stage 3	X				X

2 Materials and methods

A fatigue test was performed on the bolster beam of a railway vehicle. Five (5) cases of load were programed and implemented in three stages of the fatigue test as presented in Table 1, namely:

Case P	Longitudinal loads transmitted by the bogie to the pivot during starts and stops of the vehicle.
Case R	Vertical loads applied at the right and left dampers due to the weight of the carbody and passengers.
Case Q	Transverse load over the pivot due to the movement of the carbody during curves.
Case S	Vertical load over the secondary damper due to carbody weight and passenger weight.
Case T	Longitudinal loads transmitted by the bogie to the pivot via impacts between the pivot and the plastic limiters in the bogie.

The sections below introduce the materials and methods required to perform the fatigue test.

2.1 Experimental setup

The bolster beam was instrumented at fifteen (15) points, monitoring the deformation of the most critical weldings during the fatigue test. Both, materials used to perform the fatigue test at the product test laboratory of the Universidad EAFIT and the sensors used to collect the information are explained below.

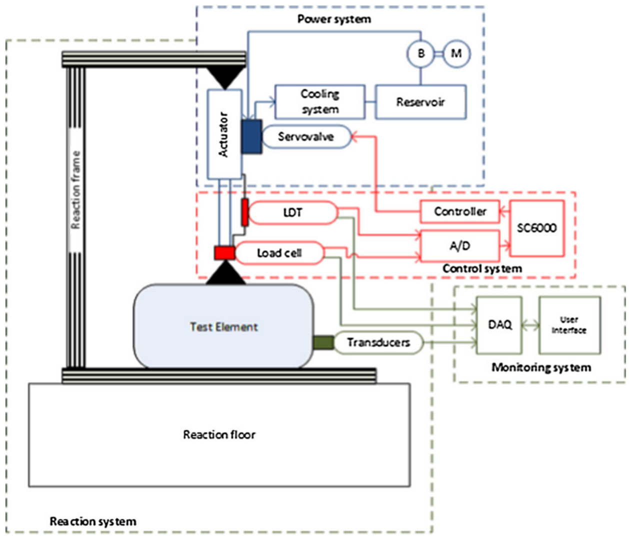

Fig. 2 Diagram of conformation of the test laboratory at testing a particular element. Four systems interacts amongst them, namely: reaction, power, control and monitoring system

2.1.1 The product test laboratory

The load test was performed using the Product Test Laboratory located at the Universidad EAFIT. It is made up four main systems as presented in Fig. 2, namely:

Reaction structure: It supports the loads applied to the specimen. It consist in a reaction frame in several configurations, a reaction wall and underframe, that permit to place the test specimen and actuators in several configurations according to test protocol.

Power system: It is composed by the set of elements required to transmit power through actuators to the test specimen. It consist of a 6CTAA8.3-G1 Cummins Motor, three actuators Shore-Western reference 922.5E designed to apply 102 kN at tension and at 167 kN compression and two actuators Shore Western reference 927E designed to apply 995 and 1500 kN [27].

Control system: Power system is governed by a SC6000 controller system, an industrial computer running a software specifically designed for this purpose by Shore Western company [26].

Monitoring system: The laboratory counts with a HBM MGCPlus equipment configured with five (5) AP815 cards devoted to deal with strain gauges signals.

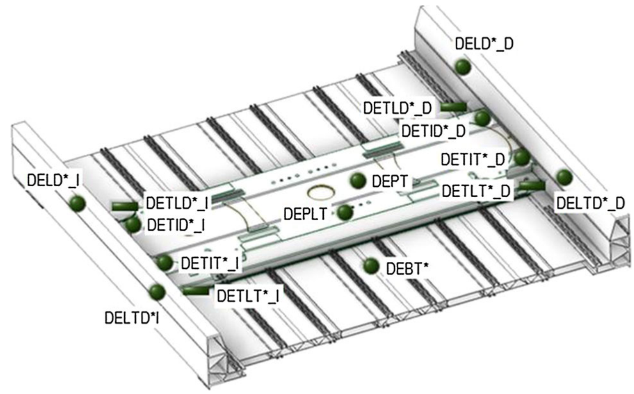

Fig. 3 Location of sensors on the bolster beam

2.1.2 Bolster beam Instrumentation

The bolster beam instrumented correspond to the element patented in [15]. It was welded and designed according to european standards [8–10]. On the other hand, two types of sensors were located across the bolster beam as presented in Fig. 3, namely:

- Thirteen (13) triaxial strain gauges reference K-RY8-3-45-120-0, one disposed in the underframe of the structure (DEBT), and the rest symmetrically at left and right side of the bolster beam at: crossbars at front and rear location (DEL{D,T}), at the top surface of the bolster beam, close to the weld that joins it with the crossbars at front and rear location (DETL{D,T}); at the frontal and rear surfaces of the bolster beam close to the welds that join it with the underframe (DETL{D,T}).
- Two uniaxial strain gauges reference HBW-35-125-6-3VR located at the pivot of the bolster beam, specifically disposed to acquire signal from longitudinal (DEPLT) and transverse (DEPT) deformations.

The relation between sensor, location type of welding and stress cycle standard curves (S-N Cycle) is presented in Table 2. It is considered that the element survives the fatigue test if the stress data collected resides below the ideal curve.

Strain signals were collected using a MGCplus device using 41 channels of acquisition and processed in an external computer.

2.2 Methods

The method followed during this study consisted in the analysis of data coming from a fatigue test performed over the bolster beam of a railway-vehicle. Three hypothesis of load were tested over the specimen. At each stage, the stress over the welds were estimated using strain information and the material characteristics. Thereafter, the results were analyzed

Table 2 Type of welding, sensor and S-N ideal curve related according to [9]

Base material	DEBT
Full penetration butt weld	DETID_I
	DETID_D
	DETIT_I
	DETIT_D
Full penetration T weld	DETLT_I
	DETLT_D
	DETLD_I
	DETLD_D
Partial penetration T weld	DETLD
	DETLT
	DELTD
	DELLD

and compared with the ideal S-N curve reported in the standard [9]. It is considered that the specimen will survive the design life if resultant stress plots undergo the ideal curve. The method overview is show in Fig. 4.

2.2.1 Load hypothesis

Three load hypothesis were implemented during the fatigue test of the bolster beam as presented in Fig. 5. Stage 1 consist in the implementation of loads during starts and stops of the train at entrance and outsides of the station (case P) and loads due to the weigh of the carbody and the passengers (case R) as presented in Table 3 during the equivalent to 18 years of operation. Stage 2 emulates the forces over the pivot during curves and (case Q) and the vertical load over the secondary damper due to the weigh of the carbody and passengers (case S) as presented in 4 equivalent to 18 years of operation. Finally, stage 3 implements extreme longitudinal loads over the pivot at the grip and bogie limiters (cases P and T) as presented in Table 5 until the presence of cracks in the specimen was confirmed by a visual inspection.

2.2.2 Signal processing

The signals coming from the strain gauges in the configuration presented in Fig. 6 were acquired at a sample rate of 300 Hz, and initially lowpass-filtered at a cutoff frequency of 7 Hz to avoid the aliasing effect and highlight the frequencies of interest and also subtracting measures obtained at zero load. Hence, the instantaneous principal stresses $\sigma_{1,2}$ at each location was computed as a combination of the strain $\epsilon_{a,b,c}$ and the Young module of the material as [16]:

$$\sigma_{1,2} = \frac{E}{1-\upsilon}\frac{\epsilon_a+\epsilon_c}{2} \pm \frac{E}{\sqrt{2}(1+\upsilon)}\sqrt{(\epsilon_a-\epsilon_b)^2+(\epsilon_c-\epsilon_b)^2}. \quad (1)$$

2.2.3 Data analysis

The signals were analyzed extracting the frequency components of interest, firstly by computing the Fourier transform of each stress signal using a flat top window of one (1) hour length and secondly, taking out the magnitude of the component excited according to the fatigue protocol at each stage. Finally, the data were plotted and compared to the corresponding ideal curve [9].

3 Results

At stage 1 were applied the equivalent to eighteen (18) years of alternate loads over the principal dampers (case of load R) and the longitudinal over the pivot in normal operation conditions (case of load P). In all cases, the stress measured is lower than the ideal curve for this type of welding reported in [9], therefore, the life span estimated for those regions is 10^9 cycles and their cumulative damage was computed as 0.0035. At the end of this stage, it was performed a visual

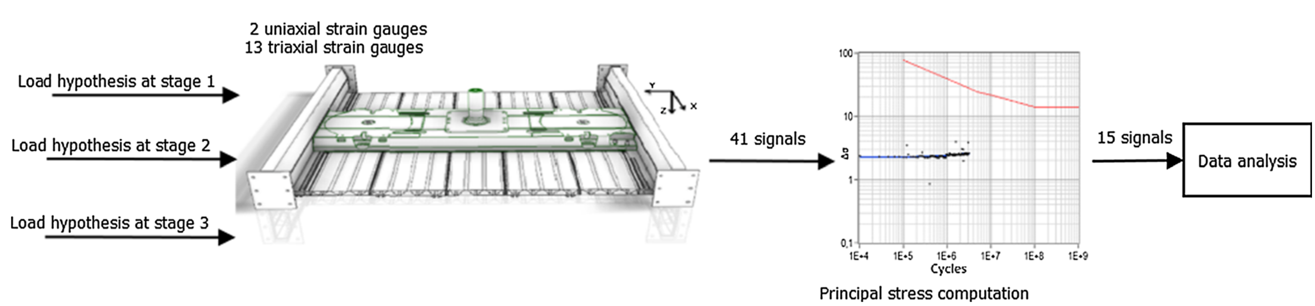

Fig. 4 Method Overview. A fatigue test was performed evaluating three different stages: *1* Vertical loads at the dampings and longitudinal load to the pivot, *2* Vertical load at the secondary damper and transverse load to the pivot and finally, *3* Extreme start and stop loads of the railway-vehicle. Data coming from several sensors were recorded, preprocessed and analyzed to obtain stresses at critical places of the structure

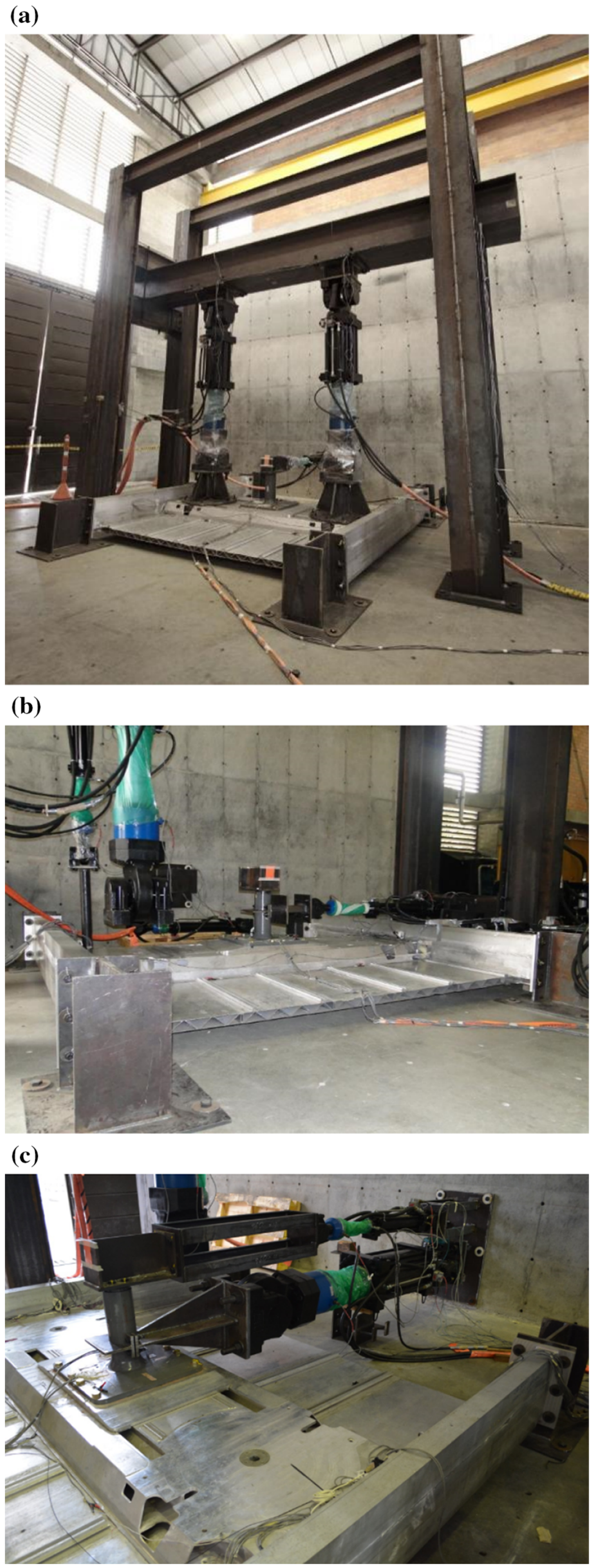

Fig. 5 Implementation of the three stages of the fatigue test. **a** *Stage 1* Load over dampers and regular starts and stops. **b** *Stage 2* Loads over the Secondary damper and transverse load on the pivot due to pass over curves. **c** *Stage 3* Critical starts and stops

Table 3 Cases of load implemented during the stage 1 of the fatigue test

Case of load	Value	
P	Maximum load [kN]	27.13
	Minimun load [kN]	−23.58
	Average load [kN]	1.58
	Frequency [Hz]	5.00
R	Maximum load [kN]	122.73
	Minimun load [kN]	58.73
	Average load [kN]	90.73
	Quasistationary load frequency	0.25
	Dynamic load frequency [Hz]	5.00

Table 4 Cases of load implemented during the stage 2 of the fatigue test

Case of load	Value	
Q	Maximum load [kN]	18.47
	Minimun load [kN]	−18.47
	Average load [kN]	0.00
	Frequency [Hz]	5.00
S	Maximum load [kN]	4.00
	Minimun load [kN]	−4.00
	Average load [kN]	0.00
	Frequency [Hz]	5.00

Table 5 Cases of load implemented during the stage 3 of the fatigue test

Case of load	Value	
P	Maximum load [kN]	64.80
	Minimun load [kN]	−64.80
	Average load [kN]	0.00
	Frequency [Hz]	1.00
T	Maximum load [kN]	214.06
	Minimun load [kN]	−214.06
	Average load [kN]	0.00
	Frequency [Hz]	1.00

inspection to confirm the absence of fissures on the bolster beam.

At stage 2 the loads applied correspond to the vertical load over the left secondary damper (case of load Q) and transverse load over the pivot (case of load S) the equivalent to the alternate loads received during eighteen (18) years of normal operation. All stresses measured resides below the ideal curves for this type of welding reported in [9], hence, the life span estimated for those regions is 10^9 cycles and their cumulative damage was computed as 0.0035. At the end of this stage, it was performed a visual inspection and also a dye

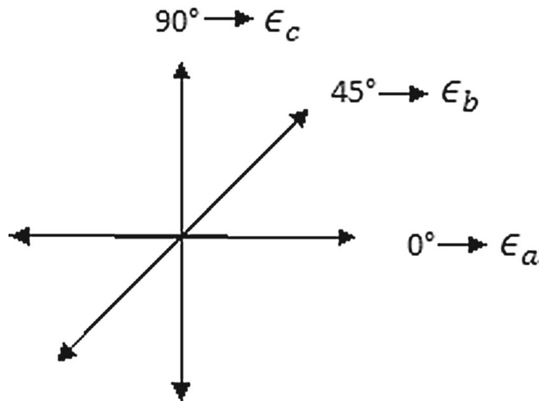

Fig. 6 Internal orientation of the triaxial strain gauges

penetrant liquid inspection to confirm the absence of fissures on the bolster beam. The cumulative damage after stages 1 and 2 was computed as the sum of cumulated damages at each stage.

The stage 3 was designed as a destructive test in which extreme starts and stops of the vehicle were considered, i.e., longitudinal loads over the pivot due to the guide rode gripper (case of load P) and the impact over the pivot with the bogie limiters (case of load T) as the loads present when the train collides with the end of line. The test was finished when the appear a crack in the pivot, after 3180 cycles. Although, the object of the test, the bolster beam, do not present fissures when evaluated with visual and dye penetrant liquids inspection.

The damage cumulated at after the fatigue test of normal conditions (stages 1 and 2) was computed following the Miner's linear rule, being d the damage cumulated during a specific cases of load i, n_i the current number of cycles applied to the specimen, and N_i the number of cycles in which the current stress value intercept he ideal curve reported in [9]:

$$d_i = \frac{n_i}{N_i}. \tag{2}$$

If the measured stress is lower than any value in the ideal curve, N is assumed as the maximum number of cycles in the scale. The cumulate damage covering all fatigue stages was computed following the Miller's linear rule as [12]:

$$D = \sum_{i \in \Omega} d_i = \sum_{i \in \Omega} \frac{n_i}{N_i}, \tag{3}$$

that is, the sum of the damage cumulated at each stage independently.

Results of cumulative damage across the three test are presented in Figs. 7, 8 and 9, namely, the stress measured at the right lateral face of the bolster beam close to the welding that joints it with the floor at DETLD_D, the stress measured at the left lateral face of the bolster beam close to the welding that joints it with the floor at the DETLD_I and the stress measured at the floor of the structure DEBT.

The stress measured at DETLD_D,I are not symmetric as the left side of the bolster beam at the rear side contains a cavity to install the left secondary damper. At the first stage, stresses of the sensors presented were in the order of 10^0 MPa. The second stage present different behaviour for each of the locations shown. The stress on the DETLD_D location decrease as the only effect over this location was the moment due to the transverse load over the pivot. On the other hand, the stress over the weld at DETLD_I presented a notable increment of stress, as the left secondary damper is acting close to this location, so, even if the load simulating the secondary damper effect is of only 4 kN, its consequences over the welds is flagrant, being a place candidate to be prioritized during inspections activities. The effect of this stage is negligible on DEBT. Finally, during the third stage, the stress at those location were maximum, but the cumulative damage received during this stage was small compared with [9], also taking into account that the bolster beam was pretested with the equivalent of 18 of operation.

4 Discussion

The bolster beam is the principal structural component of a railway vehicle, although its maintenance program consist in visual inspection separated by several years. In case of find a fissure, the corrective task consist on gouge and weld the location [1,3], however, presence of fissures at the early life of the component is a common issue in railway vehicles [3,6,29]. Moreover, materials as aluminum have a finite number repairs and then, after several welds, it is necessary to replace the entire element, being an expensive task that reduce drastically the vehicle availability [4], so the bolster beams made on this material requires of special care during its design stage to reduce those maintenance task at maximum. Full-scale mechanical tests could help to predict the most probable location of fissures and when they could appear in order to program its maintenance, increasing the reliability of the entire vehicle better than other techniques such as scale test and numerical simulation, which miss-estimates several factors [32]. However, resources to perform mechanical tests at full scale requires of facilities that are not disposable in every country.

Therefore, the Universidad EAFIT implemented a laboratory to test full scale elements which is unique in Colombia. It allows to test several load hypothesis, allowing to command simultaneously until five linear actuators. The reaction wall and floor allows to locate the tested element in several con-

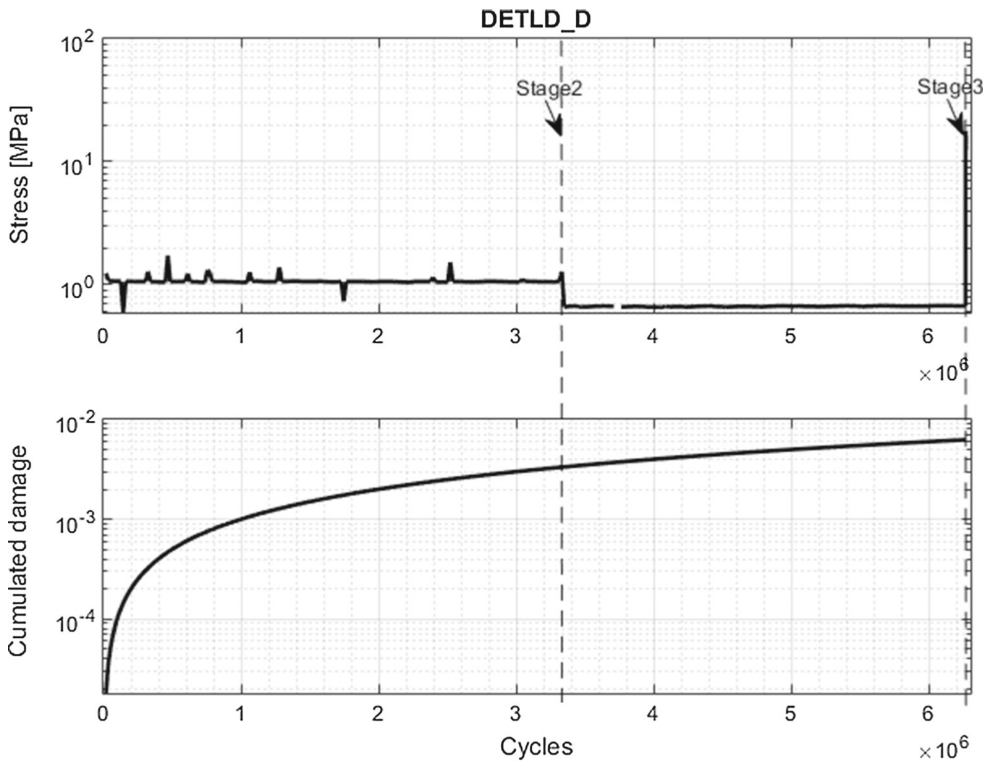

Fig. 7 Stress history at the DETLD_D location. *Top panel* shows the alternate stress measured and *bottom panels* presents the cumulated damage at each cycle

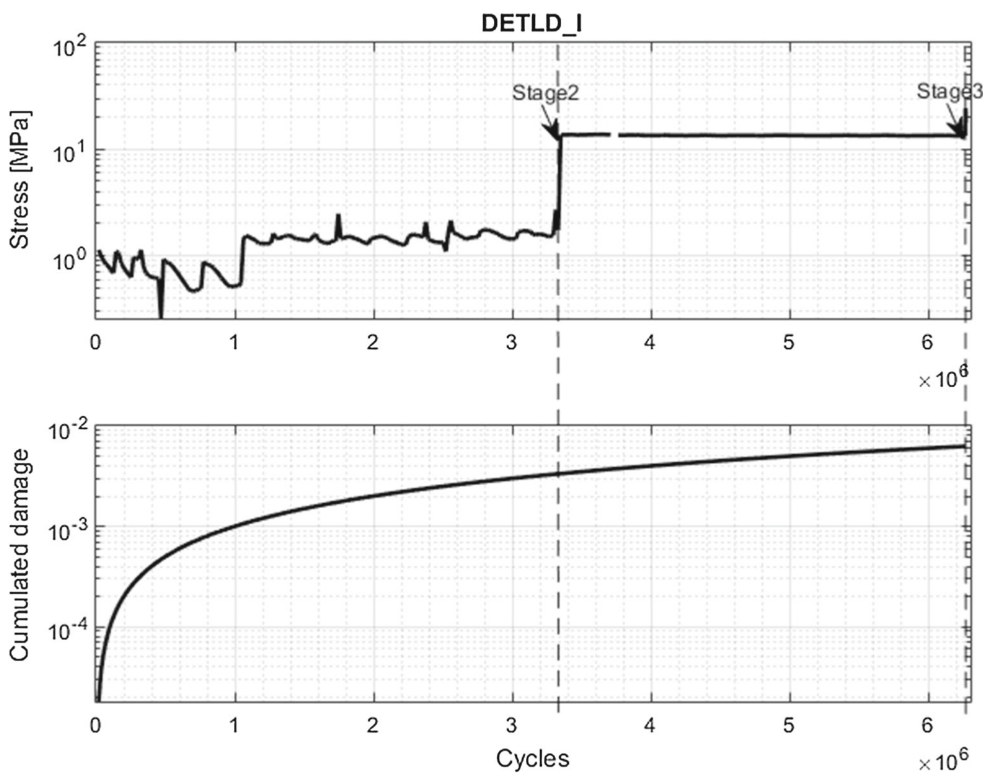

Fig. 8 Stress history at the DETLD_I location. *Top panel* shows the alternate stress measured and *bottom panels* presents the cumulated damage at each cycle

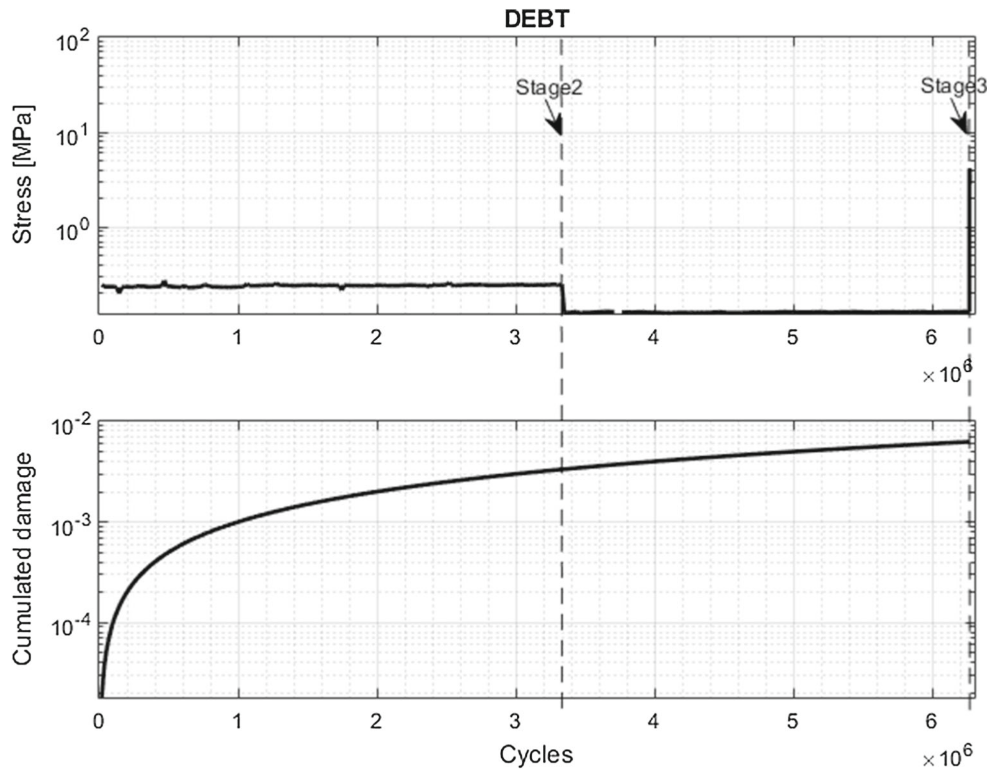

Fig. 9 Stress history at the DEBT location. *Top panel* shows the alternate stress measured and *bottom panels* presents the cumulated damage at each cycle

figurations and its controller is capable to manage complex load profiles.

The experience at instrumenting the specimen is crucial to post processing and data analysis. To instrument the specimen also in during the test and also during commercial use is a topic of research interest in mechatronics called structural health monitoring [11,17,25]. It allows to comprehend the nature of the mechanical system using electronic devices, obtain data that permit to implement maintenance programs strongly based in data analysis, machine learning and also coming back to physical interpretation. It is only possible combining the art of several disciplines as mechanics, electronics, informatics, data driven decision and automatic control in mechatronics platforms intelligent maintenance could happen. It is what EAFIT University is implementing via its laboratory, mixing together mechanical actuation, control of strength (load profile), data acquisition (instrumentation of the element) and data analysis.

Particularly, it was tested a bolster beam as case of study. In the fatigue test herein proposed, four (4) load cases were performed during a two (2) stages fatigue test on a bolster beam following the procedure planned by the laboratory of materials and construction research, institution that also supervised the test. The results of each stage were presented and the cumulative damage due to each stages was computed.

At the end of two stages of the fatigue test, i.e., all load cases were performed during the equivalent to eighteen (18) years, the bolster beam was inspected using non-destructive methods, namely: visual inspection, permeable liquids, magnetic particles and ultrasound. It was reviewed all welds present in the bolster beam and also the pivot pin. The results of such tests state that neither the bolster beam nor the pivot in presented crack or other effects that affect negatively their physical integrity during operational conditions of load. On the other hand, the pivot got fatigued before the bolster beam tested when extreme cases of load were tested.

5 Conclusion

The project herein presented the results of the full scale fatigue test performed over a new design of bolster beam of a train. Four cases of load were applied during three stages of a fatigue test corresponding to the mail loads of operation: loads due to weigh to the carbody and passengers over the principal and secondary dampers, loads due the pass over curves and loads due to starts and stops of the train. The specimen survive not only the eighteen years of work of design in normal conditions, but also a destructive test that yields in a crack on the pivot, i.e., the interface element between the carbody and the bolster beam.

Acknowledgements The authors want to acknowledge the Metro de Medellín for providing part of the data from the Project "Repotenciación (Refurbishing) de coches de vehículos ferroviarios. Caso; Optimización de la traviesa del pivote como elemento tecnológico principal de la caja de pasajeros", which was essential to develop this study.

References

1. Abid, M., Waqas, L.: Analysis and redesign of bolster beam of the bogie frame of a locomotive. J. Eng. Res. **1**(1), 271–287 (2013)
2. Åkesson, B.: Fatigue Life of Riveted Steel Bridges, chap. Full-scale Fatigue Tests of Riveted Girders. Taylor & Francis, Abingdon (2010)
3. Aristizabal, M., Barbosa, J.L., Betancur, G.R., Castañeda, L.F., Źółtowki, B.: Structural diagnosis of rail vehicles and method for redesign. Diagnostyka **15**(3), 23–31 (2014)
4. Bäckström, M.: Multiaxial fatigue life assissment of weld based on nominal and hot spot stresses. Ph.D. thesis, Lappenranta University of Technology, Lappeenranta, Finland (2003)
5. Baek, S.H., Jeon, J.H., Lee, K.Y., Cho, S.S., Joo, W.S.: Reilability analysis and pereventive maintenance for fatigue life of end beam for un-covered freight car. Trans. Korean Soc. Mech. Eng. **29**(5), 495–502 (2005)
6. Barke, D., Chiu, W.K.: Structural health monitoring in the railway industry: a review. Struct. Health Monit. **4**(1), 81–94 (2005). doi:10.1177/1475921705049764
7. Blom, A.F.: Spectrum fatigue behaviour of welded joints. Int. J. Fatigue **17**(7), 485–491 (1995)
8. EN/ISO: EN/ISO 14731: Welding coordination tasks and responsibilities (2006)
9. EN/ISO: EN/ISO 1999-1-3: Design of aluminium structures - part 1-3: Structures suceptible to fatigue (2007)
10. EN/ISO: EN/ISO 14732:2013: Welding personnel—qualification testing of welding operators and weld setters for mechanized and automatic welding of metallic materials (2013)
11. Farrar, C.R., Worden, K.: An introduction to structural health monitoring. Philos. Trans. R. Soc. A **365** (2007)
12. Fatemi, A., Yang, L.: Cumulative fatigue damage and life prediction theories: a survey of the state of the art for homogeneous materials. Int. J. Fatigue **20**(1), 9–34 (1998)
13. Fischer, X., Coutellier, D.: Editorial. Int J Interact Des Manuf (IJIDeM) **1**(1), 1–4 (2007). doi:10.1007/s12008-007-0007-3
14. Goo, B., Sco, J.W.: Probabilistric fatigue life evaluation of rolling stock structures. Trans. Korean Soc. Autom. Eng. **11**(5), 89–94 (2003)
15. Heredia, L.F.C., Pérez, J.L.B., Cano, M.A., Naranjo, J.R.T., de Jesús Sánchez Vélez, H., López, M.E.P.: Traviesa para vehículos ferroviarios de pasajeros, procedimiento de ensamble de la misma y método para disponerla en una carrocería de vehículos ferroviarios (In process)
16. Hoffmann, K.: An Introduction to Measurements using Strain Gages. Hottinger Baldwin Messtechnik GmbH, Darmstadt (1989)
17. Liang, J.Y., Deng, X.J.: Structural Heatlh Monitoring 2015: System Reliability for Verivication and Implementation, chap. Applications of Structural Health Monitoring on Intelligent High-speed Train, pp. 2037–2045 (2015)
18. Luo, R.K., Wu, W.X., Cook, P.W., Mortel, W.J.: An approach to evaluate the service life of rubber springs used in rail vehicle suspensions. Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit **218**(2), 173–177 (2004). doi:10.1243/0954409041319597
19. Martinod, R.M., Betancur, G.R., Restrepo, J.L., Castañeda, L.F.: Structural analysis of railways bolster-beam under commercial operation conditions: over-traction and over-braking. Probl. Transp. **11**(2), 67–77 (2016)
20. Paget, C., Speckmann, H., Krichel, T., Eichelbaum, F.: Validation of SHM Sensors in Airbus A380 Full-Scale Fatigue Test. Wiley, Newyork (2009). doi:10.1002/9780470061626.shm149
21. Pellicciari, M., Andrisano, A.O., Leall, F., Vergnano, A.: Engiengine method for adaptive manufacturing systems design. Int. J. Interact. Des. Manuf. (IJIDeM) **3**, 81–91 (2009). doi:10.1007/s12008-009-0065-9
22. Qiu, L., Yuan, S., Bao, Q., Mei, H., Ren, Y.: Crack propagation monitoring in a full-scale aircraft fatigue test based on guided wave-gaussian mixture model. Smart Mater. Struct. **25**(5), 055 (2016)
23. Ruitenburg, R.J.R., Braaksma, A.J.J., van Dongen, L.A.M.: A multidisciplinary, expert-based approach for the identification of lifetime impacts in asset life cycle management. In: 3rd international conference on through-life engineering services, vol. 2014, pp. 204–212 (2014)
24. Schlake, B.W., Todorovic, S., Edwards, J.R., Hart, J.M., Ahuja, N., Barkan, C.P.L.: Machine vision condition monitoring of heavy-axle load railcar structural underframe components. Proc. Inst. Mech. Eng. Part F: J Rail Rapid Transit **224**(5), 499–511 (2010)
25. Seo, J., Hu, J.W., Lee, J.: Summary review of structural health monitoring applications for highway bridges. J. Perform. Constr. Facil (2015). doi:10.1061/(ASCE)CF.1943-5509.0000824
26. Shore Western Manufacturing Inc., 225 W. Duarte rd. Monrovia, CA 91016: SC6000 Operation Guide v8.2.39, System Overview (2014)
27. Shore Western Manufacturing Inc., 225 W. Duarte rd. Monrovia, CA 91016: User Manual 92XE Series Linear Actuators, v20140728 edn. (2014)
28. Smith, K.B., Parker, E.S., Iler, D.J.: Railcar service spectra generation for full-scale accelerated fatigue testing. Appl. Autom. Technol. Fatigue Fract. Test. Anal. **4**, 62–84 (2002)
29. Song, Z., Fang, S., Zhang, Y., Xie, J.: Cracking analysis of bolster cover pate in c70 freight wagons. Eng. Fail. Anal. **30**, 43–60 (2013)
30. Tremblay, R., Léger, P., Rogers, C., Bouaanani, N., Massicotte, B., Khaled, A., Lamarche, C.P.: Experimental testing of large scale structural models and components using innovative shake table, dynamic, real-time hybrid simulation and multi-directional loading techniques. In: Proceedings of the 3rd international conference on advances in exp. struct. eng (2009)
31. Tuomi, R.L.: Full-scale testing of wood structures. In: Schriever, W.R. (ed.) Full-scale load testing of structures. ASTM STP 702. ASTM, Philadelphia, PA, pp. 45–62 (1980)
32. Yamamoto, M., Makino, K., Ishiduka, H.: Comparison of crack growth behaviour between full-scale railway axle and scaled specimen. Int. J. Parasitol. Fatigue **92**(1), 15–22 (2016)