STRUCTURAL DIAGNOSIS OF RAIL VEHICLES AND METHOD FOR REDESIGN

Mauricio ARISTIZABAL*, Jaime L. BARBOSA*, German R. BETANCUR*,
Leonel F. CASTAÑEDA*, Bogdan ŻÓŁTOWSKI**

* Universidad EAFIT, Grupo de Estudios en Mantenimiento Industrial (GEMI)
Carrera 49 N° 7 Sur – 50, Medellín Colombia, e-mail: maristi7@eafit.edu.co
**University of Technology and Life Sciences in Bydgoszcz, Poland

Summary

Structures of rail vehicles are designed for a useful structural life of 30 years. However, structural problems which reduce the mechanical performance of the structure might appear due to normal operation conditions and, in some cases, make it unsuitable for a safe operation. This document presents the structural diagnosis of a metro system and the method for the redesign of structural elements of rail vehicles that was derived from this diagnosis, so that the structural performance of both the element and the whole structure is improved. It is based on the European standards related with aluminium and railway applications, and considers the necessary aspects to produce a safe solution for the final design.

Keywords**:** structural diagnostic, redesign; rail vehicles; bolster beam; fatigue; aluminium.

DIAGNOZOWANIE KONSTRUKCJI POJAZDÓW KOLEJOWYCH
I SPOSÓB ICH PRZEPROJEKTOWANIA

Streszczenie

Konstrukcje pojazdów szynowych przeznaczone są na okres eksploatacji 30 lat. Problemy użytkowania zmniejszają wydajność konstrukcji, co może pojawiać się z powodu anormalnych warunków eksploatacji i sprawia w niektórych przypadkach, że pojazd nie nadaje się do bezpiecznej eksploatacji. W tej pracy przedstawiono diagnozę strukturalną elementów systemu „metra" i sposób przebudowy elementów konstrukcyjnych pojazdów szynowych, które wynikają z diagnozy. To powoduje, że wydajność strukturalna elementu i całej konstrukcji jest lepsza. Całość postępowania jest oparta na europejskich standardach związanych z aplikacjami aluminium w kolejnictwie i wskazuje na niezbędne aspekty produkcji bezpiecznych rozwiązań dla końcowego efektu.

Słowa kluczowe: diagnostyka strukturalna, przeprojektowanie; pojazdy szynowe; wzmocnienia wiązki; zmęczenie; aluminium.

INTRODUCTION

Design of new structural elements for rail vehicles, (e.g. car body and bogie frame), usually seeks a useful life of 30 years [5]. However, due to the different conditions that arise in normal operation, it is common to require corrective maintenance procedures on structural elements in order to safely guarantee the established design life.

Normal operation of the vehicle represents complex loading conditions for the structural elements. Its dynamic behaviour represents a very load-alternating environment for the different parts, so that fatigue problems are usual in rail vehicles, especially in those with aluminium structures. Fatigue problems are represented by formation of cracks.

Although some cracks might be admissible for a safe operation of the vehicle, continuously growing cracks, located in critic connections are not admissible and requires corrective actions, such as refurbishment procedures [28,29,30].

Current computational tools allow foreseeing a wide range of structural problems due to high accuracy of the geometry and wide variety of conditions that can be simulated. As a consequence, newer designs are thought more efficiently. Material, shape and connections can be easily modified in the computational tool to obtain an optimum design, saving time and optimizing expenses. Although earlier designs (previous to the computational era of 1990's) used computational tools for structural analysis, they did not include such advantages and therefore structural problems are more usual.

Also, knowledge about fatigue theories and fatigue behaviour of several aluminium materials was not completely developed. This led to structures that might have both elements sufficiently designed for the operation conditions and elements that cannot safely operate the estimated design life. As a result, redesign of structural components represents an efficient way to guarantee a safe operation of the vehicle along its remaining life [27,28].

In addition, modernization projects are usual in the rail industry since their goal is to extend the design life of the vehicles. Evolution and rise of public transportation utilization makes it necessary to increase the number of vehicles available (Fig.1). Also, another goal is to install more efficient components that optimize both energy and economical expenses. As a result, redesign processes are also a proper way to extend the remaining life of the whole structural element.

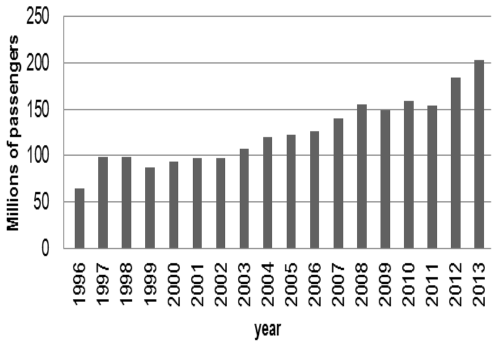


Fig.1. Total passenger flow for Metro de Medellin public transportation system from 1996 to 2013

This document presents a diagnosis of the structural behaviour of a rail vehicle, and consequently a method to redesign structural elements for rail vehicles made of aluminium alloys. It is mainly focused on projects that intend to replace structural elements and refurbish rail vehicles. For this, it presents the European standards related with the redesign process and presents advantages and disadvantages of developing redesign processes with aluminium structures.

1. DIAGNOSIS OF STRUCTURAL BEHAVIOR OF A RAIL VEHICLE

This study is applied to passenger vehicles belonging to the mass transport railway vehicle fleet of Medellín city (Colombia), which is a railway system similar to suburban trains. The original equipment manufacturers of rolling stock were Maschinenfabrik Augsburg-Nürnberg (MAN) for mechanical components and Siemens for electrical components. MAN has since become Adtranz company and subsequently Bombardier Transportation. The vehicles are similar in geometry and design to the ET420 train sets formerly operated by Deutsche Bahn in commuter service (e.g. the Munich S-Bahn) [24]. The railway system has 42 three-unit cars (Fig.2). Each car has two bogies that are supported over two axle–wheel sets. Each car has a suspension of two stages: primary and secondary [25,26,27,28].


Fig.2. Railway vehicle, unit of three cars

The bolster beam transfers all vertical, longitudinal and transversal loads between the bogie and the carbody. It is an element built in aluminium alloy AlZn4.5Mg1F35, series EN AW 7020 T6, with stress limit of 350MPa and yield stress 290Mpa [11], composed by four extruded profiles welded together, one superior, and three in the bottom side – one central and two laterals. The bolster beam has four ducts that transversely pass through, to allow the pneumatic pipes to cross from one side to another –on the extremes of the bolster pivot beam and also the electrical cables in the centre. The bolster beam is reinforced with angle brackets assembled through welds.

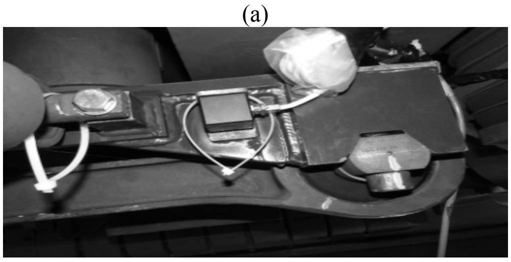
A motor car is instrumented, choosing a train according to the following rules: i. a vehicle without unconformities after the last maintenance; ii. a vehicle that is not close to a major maintenance; iii. vehicles without rare elements attached to the pivot beam (it could be a repaired vehicle); and iv. without live load (vehicle in opration conditions).

The bolster pivot beam has been implemented heading to the direction of the running of the train, X. A set of measurements has been established, directly related to the dynamic behaviour of the bolster pivot beam (Table 1), and composed by the record of four (4) signals - speed, strain and accelerations - (Fig.3).

Table 1. Description of the measurement set for the experimental tests.

Sensor	Element	Measurement point	Dir.	Nam.
Speed	Axle box	Train	X	V
Uniaxial strain gauge	Bolster beam	Region near to the through-holes	Y	D3T
Uniaxial strain gauge	Bolster beam	Region near to he through-holes	Z	D3V
Acceleration	Pivot column	Centre of the plate	X	A7L

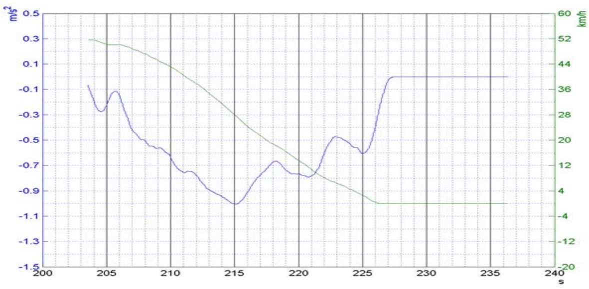
(a)



(b)

Fig.3. Location of sensors - (a) strain gauges, (b) tri-axial accelerometer

Fig. 4 presents acquired signals in two scenarios: i. entering a station and ii. leaving the station, identified as the most critical conditions for the stress distribution of the bolster beam. During the process of braking, deceleration is near to 1.0 m/s^2, while in traction process the acceleration is 0.9 m/s^2. During braking, a peak strain was measured of 255 um/m in Y direction (transverse) and 225 um/m in Z direction (vertical). This maximum occurs in a change of acceleration. During acceleration, the maximum strains occur just when maximum acceleration is reached, values close to 140 um/m in Y direction and 63 um/m in the Z direction were obtained.



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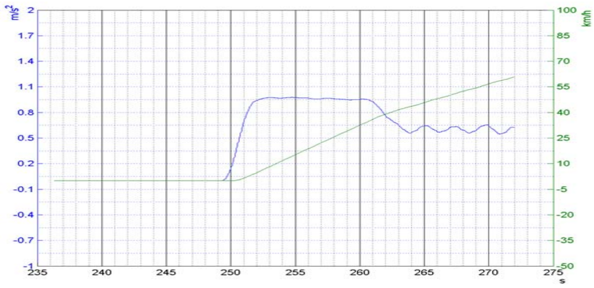

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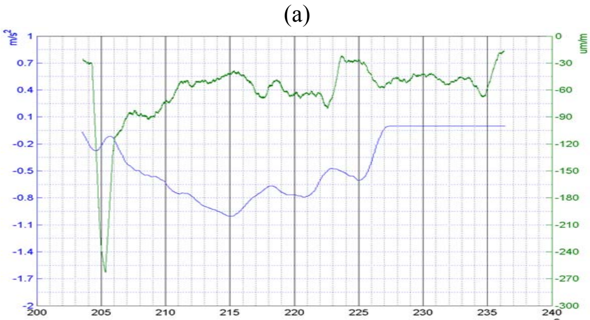

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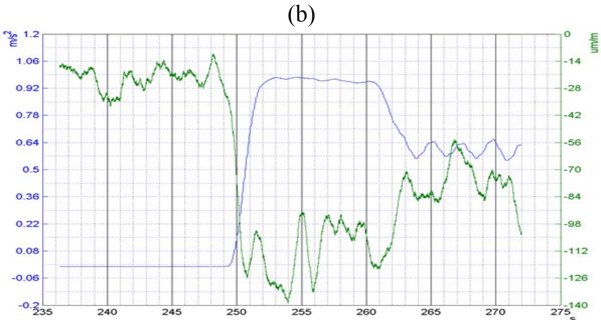

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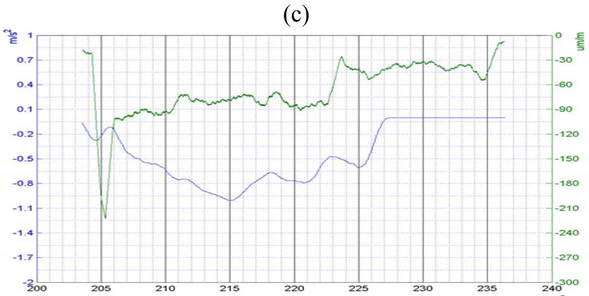

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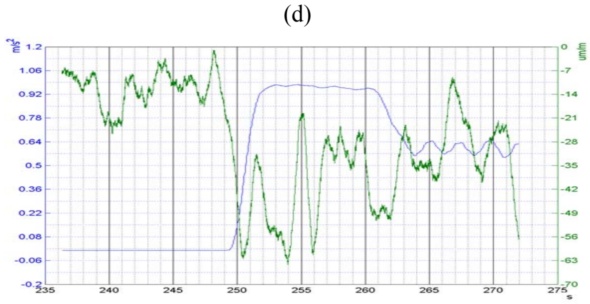


(f)

Fig.4. Signals in time domain - (a) Acceleration and velocity at entrance to the station, (b) Acceleration and velocity at exit the station, (c) D3T and acceleration at entrance to the station, (d) D3T and acceleration at exit the station, (e) D3V and acceleration at entrance to the station and (f) D3V and acceleration at exit the station

The status of the stress in the bolster beam has been determined for each one of the traction and braking events in the running of the vehicle. In order to present an example of the results – Fig.5 - shows a Von Misses strain distribution, applied over the main region of the pivot beam and the union region with the lateral floor structure. It is observed that over the pivot axle –made in steel– the strains are concentrated in the region where it is united with the plates to the pivot beam. Nevertheless, the maximum strains are presented over the exterior surface of the lateral plate –made in aluminium–, specifically in the region of the outline of two longitudinal through-holes –holes that have the purpose to serve the canal to ducts that the train possesses. Those holes belong to the pivot beam and work as strain concentrators. Fig. 6 presents in detail the deformation distribution under commercial operation conditions of traction and braking.

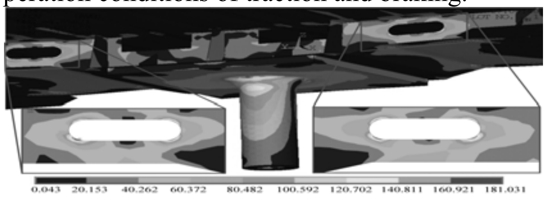
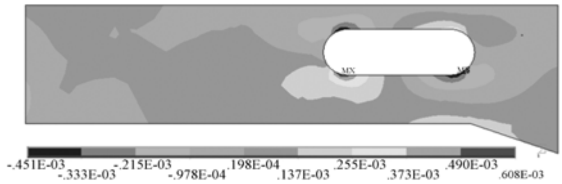
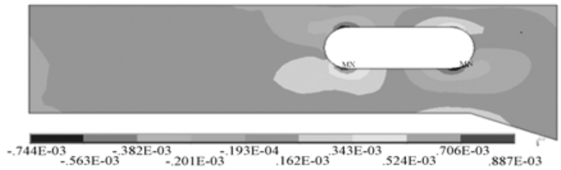


Fig. 5. Strain distribution (Von-Misses) [MPa]



(a)



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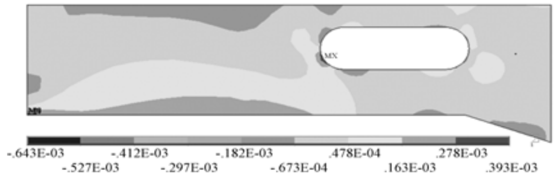

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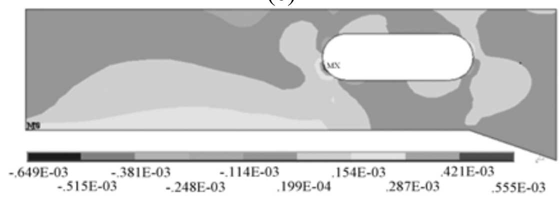

(d)

Fig.6. Deformation distribution in the strain concentrators [(a) Braking, Y direction, (b) Traction, Y direction. (c) Braking, Z direction and (d) Traction, Z direction]

As a consequence, this element present a critical behavior due to its load condition. It is clear that the ducts are stress concentrators. Hence, for an extension in the life of the elements, a refurbishment of the bolster beam is necessary to extend the life of the vehicles.

2. METHOD FOR REDESIGN ALUMINUM STRUCTURAL COMPONENTS OF RAIL VEHICLES

Redesign projects are usually performed for the following reasons:

- problems of normal operation conditions: cracks, excessive wear and others;
- refurbishing and modernization projects: extend the design life of a structure;
- improvement of a current design to produce a new fleet.

As a result, the following procedure must be considered to realize the project:

I. Part identification.
II. Cause detection.
III. Proposals evaluation.
IV. Detail design and formal evaluation.
V. Manufacturing and testing.

All those steps are guided by the European standards listed in Table 2.

Table 2. European standards involved in the redesign of aluminium structural components of rail vehicles.

Standard	Description
EN 485 [7]-[9]	Establishes the mechanical properties of the aluminium alloys for plates and sheets.
EN 755 [10] - [13]	Establishes the mechanical properties of the aluminium alloys for extruded profiles.
EN 1999 [14], [15]	Establishes design parameters for aluminium structures, including joint and fatigue properties.
EN 12663 [16], [17]	Establishes the structural requirements of the car bodies of railway vehicles and its evaluation methodology.
EN 15085 [18] - [22]	Related to welding procedures for railway vehicles.
EN 15663 [23]	Establishes the design and operation masses for the design of railway vehicle components

2.1. Part identification

Maintenance history of the vehicles usually shows critical parts that are selectable for a redesign procedure. In structural matters, cracks are the usual effects of structural failures in railway vehicles (Fig.7). If no cracks were detected during the operational life of the vehicles, a full inspection using Non-Destructive Testing (NDT) must be performed to detect elements that have a redesign potential, understood as the requirement to replace an element because it represents (or will represent) an issue for the safe operation of the vehicle.

Fig.7. Cracks on a bolster beam of a Metro system

Typically, cracks are located near welded regions, since those regions are critical in dynamic conditions. However, design problems might arise in base material parts as well, when vibrations, collisions and activities are present in the normal operation of the vehicle.

2.2. Cause detection

In order to detect the causes of the structural failures, both a technical diagnostic using experimental measurements and a formal structural analysis must be performed. The analysis must contain both static load cases with critical combinations, and also dynamic load scenarios. Finite element analysis presents a proper method to evaluate structural performance, however it is subject to normal computational inaccuracies, due to simplifications. A proper model should be developed, and possibly validated with experimental measurements in order to produce conclusive results.

The causes are usually alternating loads that exceeds the mechanical fatigue properties of the materials. As a result, loads that varies on time (vertically, longitudinally and transversally) should be evaluated. The following subsections present a static approach and dynamic approach for the analysis.

2.3. Influence of material

Aluminium structural components are characterized by is high strength-to-weight ratio. However, different characteristics associated with both temper and fatigue behaviour decreases its usability since joint procedures drastically reduce the mechanical performance.

Tempered alloys such as zinc alloyed series (EN AW 7XXX) and copper-zinc alloyed series (EN AW 2XXX) have the highest mechanical properties regarding static strength, fatigue strength and hardness. However, those alloys present more challenges in its manufacturing processes since joint connections using rivets or bolts generate stress concentrators and therefore local weakening; and welded connections must be avoided since its mixing capability with filler materials do not present acceptable results, producing weak joints.

Tempered silicon-magnesium alloyed series (EN AW 6XXX), magnesium alloyed series (EN AW 5XXX) and silicon alloyed series (EN AW 4XXX) present good structural performance, while preserving a better welding capability. These alloys are the most used in the rail industry, since they present a wide range of presentations (plates, sheets, extruded profiles and castings). This make them easier to manufacture in complex shapes, so that different parameters such as weight, structural strength structural safety and production costs are optimum.

Earlier designs involved other materials with high strength values, such as EN AW 7020 T6. However, fatigue cracks were common in those designs, since this materials presents both welding problems and stress corrosion [14]. Fig. 8 shows the material composition of a metro wagon, designed and manufactured in 1980's.

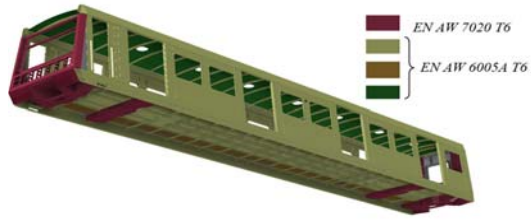

Fig. 8. Material composition of the car body of a Metro coach, built in 1980's

Now the principal structural parts for rail vehicles are made out of silicon-magnesium alloys. Structural parts like the carbody underframe, lateral walls and so on, are made of medium-high strength alloys such as EN AW 6005A T6. Parts that require higher structural strength are made of EN AW 6082 T6, such as coupler, front wall, end walls, window sills and so on. These alloys present good welding capability, good structural strength for both static and fatigue loads.

2.4. Fatigue behaviour

Fatigue is known as the failure of a structural component due to the variation of the load condition over time. As explained in [1], fatigue is dependant in the number and magnitude of load variations that applies to a structural element, hence related to the stress variation. The stress range at which the elements fails decreases with a greater amount of load cycles.

As opposed to common steel elements, aluminium alloys do not present a defined endurance limit. This means that aluminium alloys will always fail, even if the stress range reach a low value. As a result, aluminium structures design is based on a cumulative damage calculation [1], so that, the design establishes a design life goal, and therefore all elements must be capable to withstand at least this number of cycles.

2.5. Joint weakening

Behaviour of aluminium components depends on its joint procedures. As a static matter, joint connections such as rivets and bolts require to drill holes on the material that produce stress concentrators. This causes that small loads produce a high impact on the elements. An advantage of riveted or bolted connections is that they produce easily exchangeable assemblies.

Regarding welded joints, the structural behaviour at the joints is critically reduced in the region next to the weld bead, the Heat Affected Zone (HAZ). For thermally tempered alloys, due to the thermal variations in the region close to the bead, mechanical properties in the HAZ are reduced to values corresponding a non-tempered material (around 50% of the tempered values).

The most affecting factor for fatigue behaviour, is the final shape of the joint. Better fatigue performance is present when smoother shapes are obtained. Some techniques and studies have been developed [2] so that better results are obtained in fatigue performance. A sketch of this procedure is shown in Fig. 9, where the termination of the weld bead is grounded to reduce stress concentration.

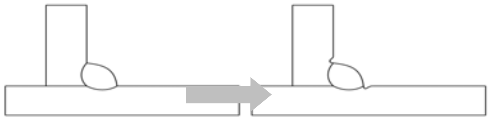

Fig.9. Machining after generation of weld bead in order to reduce stress concentrators

Some weld types in which internal termination is not appropriate might affect the structural performance of the joints as well. Fig. 10 shows a close-up on the geometry of a single side fillet weld.

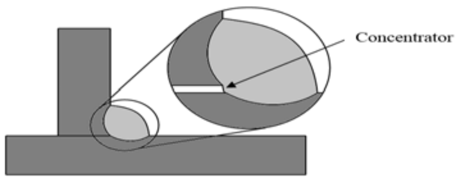

Fig.10. Stress concentrator on a fillet weld due to a gap between the two joint elements

Fig. 11 presents a comparison between some weld types shown in [15]. A single fillet welded joint (12-3.4) is the most critical welded joint, which might reduce performance in 83% compared with base material (71-7). Also, butt welds (36-3.4) are the greatest performing welds, with only 50% of mechanical performance reduction. Other weld positions, such as double sided fillet weld (25-3.4) present a better structural behaviour than the fillet weld.

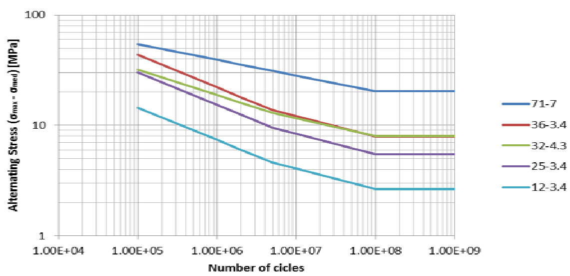

Fig.11. Whöler curves for different weld joint categories [15]

3. STATIC ANALYSIS

The static load cases are useful to isolate independent loads that might cause damage to the structure, and therefore determine a main goal for the redesign process. An example of static load cases are:

a. maximum Lateral acceleration;
b. maximum Longitudinal acceleration;
c. maximum payload (vertical load);
d. maximum lateral wind.

The standard EN 12663 [16] establishes the following static load cases to be evaluated for the design of new railway vehicles. As a result, those load scenarios are useful to synthetize maximum operating loads. However, those loads does not represent the complete operation conditions of the vehicle. Hence, fatigue load cases must be evaluated as well. A total of 14 static load cases are described in [16], which are listed is Table 3.

Table 3. Static load cases described in EN 12663-1 [16].

Load Case	Description
A	Longitudinal static loads for the vehicle body: Compressive force at the coupler level.
B	Longitudinal static loads for the vehicle body: Tensile force at the coupler level.
C	Longitudinal static loads for the vehicle body: Compressive force at the level of the waistrail (Window sill)
D	Longitudinal static loads for the vehicle body: Compressive force at the level of the cant rail
E	Vertical static loads for the vehicle body: Maximum operating load.
F	Vertical static loads for the vehicle body: Lifting at one end.
G	Vertical static loads for the vehicle body: Lifting at both ends.
I	Superposition of static load cases: Compressive force and vertical load
J	Superposition of static load cases: Compressive force and min. vertical load
K	Superposition of static load cases: Tensile force and vertical load
L	Superposition of static load cases: Tensile force and min. vertical load
M	Proof load cases for equipment attachments: Accelerations in x-directions (Bogie)
N	Proof load cases for equipment attachments: Accelerations in y-directions (Bogie)
O	Proof load cases for equipment attachments: Accelerations in z-directions

3.1. Fatigue analysis

Due to the complexity of the normal operation conditions (dynamic load scenarios), they present a more accurate way to determine structural failure causes, because they present load variations that cause fatigue in the material.

Standard [16] presents 3 load cases to be evaluated as dynamic load scenarios. Those load cases represent a separation of loads in the three principal directions in which the elements might vary loads. As a result, the study must evaluate the total damage of an element, combining the wear that the structure suffers as a result of all 3 load cases.

Table 4. Fatigue load cases described in EN 12663-1 [16].

Load case	Description
P	Fatigue loading: Longitudinal loads
Q	Fatigue loading: Transversal loads
R	Fatigue loading: Vertical loads

This load cases present variations of static load cases. As a result, other problems arising from the interaction between the different parts, such as damper forces and collisions might not be taken into account. This dynamic load scenarios might be determined using experimental measurements during normal operation conditions. They represent the most accurate procedure to determine the real loads on the structure. However, because of the costs, time consumption, and data storage that might require normal measurement procedures, selectable conditions are chosen for the measuring campaign, so that "most critical" conditions are measured.

However, these conditions might not include parameters such as the variation of element wear: bogie wear, track wear and others, might not be taken into account, and therefore present inconclusive results.

For this reason, dynamic simulation is useful for this kind of situations, in which different conditions must be evaluated. Multi-Body Simulation (MBS) is a commonly used methodology to evaluate dynamic behaviour. However, as other computer-based analyses, it might suffer for unwanted simplifications, so that the model is not sufficiently accurate. As a result, the following procedure is presented to determine a proper dynamic model:

a. Develop a dynamic model of the vehicle, considering geometric and mass conditions.
b. Perform experimental measurements to determine different parameters such as: Vibration modes, forces acting on the vehicle and track information.
c. Validate the dynamic model: Compare experimental with computational results. If necessary, adjust (detail) the dynamic model so that experimental and computational results sufficiently match.
d. Simulate isolated dynamic conditions, such as curved segments (with different radius), straight segments, approach and exit from station. Other situations might apply, such as elevations, transitions, railway splitters and others.

3.2. Proposals evaluation

Usually in a design procedure, different ideas are evaluated in order to have a bank of solutions for the problem. To optimize this phase, the proposals must be evaluated using the main load case cause of the problematic. As a result, its evaluation depends only on the most critical load cases that were found, using simple geometry. A complex evaluation usually does not contain a very detailed geometry, it contains a simple fatigue analysis for comparison purposes, and details such as welds, rivets and so on does not need to represent a very accurate model to the final object.

This evaluation should compare:

- Structural behaviour under the load case: The stress should be reduced or translated from a critical spot (such as a welded region).
- Manufacturability: Some designs might require manufacturing processes that are not suitable for the real production of the components. Other aspect for this evaluation is the requirement to produce the manufacturing tools, such as extrusion dies, that might not be suitable for production.
- Assembly capability. A determination that the element can be assembled as proposed must be performed.
- Influence on other elements. Perhaps the most important evaluation is to estimate the most important effects on the rest of the structure after performing the required modification. Structural performance of the rest of the structure must improve form the previous condition, since the structure holds a prescribed wear due to the years of operation
- Costs: Evaluation of effectiveness of the investment shall be evaluated.

3.3. Detail design and formal evaluation

In order to perform a successful design of the component, accurate analyses and detailed description should be considered. The whole design shall be in accordance with railway applications standards, despite designing elements for "used" structures.

For aluminium applications, the principal design characteristics and considerations must be in accordance with EUROCODE 9 guidelines (EN 1999). However, design of welded connections shall be guided by EN 15085, and those standards referenced in it.

Welds must be avoided. As described before, welds represent the most critical regions in aluminium designs. Not only because of its structural performance, but because its manufacturing effects (shrinking, deformation, etc). Therefore, the best weld for an aluminium structure is the one that does not exist. However, when there is a not critical region, or that it is necessary to create a joint between elements, butt welds with backings shall be considered at first into account.

Fillet welds must be avoided. Only if the structure will not be subject to critical dynamic loading, this type of tee joint might be included into the design.

In order to simulate the most accurate conditions, a detailed FEM model should be taken into account. All geometry of the structure must be included, since not only the redesigned element is evaluated, but its influence on the whole structure. As a result, for redesign processes of carbody elements, the whole carbody must be simulated.

Relevant load cases in [16] must be considered. Also, the dynamic evaluation of the vehicle (from experimental measurements or dynamic model) shall be taken into account, if they present a more critical scenario.

A faceable and cost efficient manufacturing process must be determined. Extrusion processes are well known manufacturing process, that avoids welds and are easily configurable to translate weld points to butt welded regions or lower stress regions. Also casting procedures are feasible procedures, but too complex shapes might not be possible to be faceable.

3.4. Manufacture and testing

Manufacture of the element should follow the prescribed standards. Weld qualification, quality and inspection should include parameters described in EN 15085 [18]-[22].

Although not strictly necessary, static and dynamic tests on the redesigned element without being assembled in the vehicle are useful to claim a successful design. However, costs might be increased significantly. Hence, testing might be performed only after assembling on the structure.

Experimental measurements on the assembled element to the whole structure should be performed to corroborate the. According to the structural analysis, the most affected parts shall be measured and compared in order to both validate the structural integrity of the vehicle and validate the computational model [27-30].

4. CONCLUSIONS

The present article presents the structural diagnosis of the vehicle bolster beam implemented on a metro system. The structural diagnosis clearly shows stress concentration regions and justifies that the main causes for this concentration are the longitudinal loads due to its high stress influence and high load variation.

In order to extend the vehicle life, a refurbishing process is required. As a consequence a method for redesigning structural parts for rail vehicles made of aluminium is proposed. The whole process is influenced by the European standards that are focused on aluminium and railway applications.

This method is useful for both, the redesign of a current structure in order to produce new vehicles with better mechanical performance, and projects that intend to improve the performance of "used" vehicles.

The main considerations that are presented in this method are: joint optimization, so that weakening of the structure is avoided; integration of computational tools and experimental measurements so causes and solutions of the structural problems are correctly determined.

5. ACKNOWLEDGEMENTS

This project is founded by Universidad EAFIT, Metro de Medellín Ltda and Colciencias, under the research project "Repotenciación (refurbishing) de coches de vehículos ferroviarios. Caso; Optimización de la traviesa pivote como elemento tecnológico principal de la caja de pasajeros", with code: 121656235712

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