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LEAN DEVELOPMENT METHODOLOGY FOR DURABILITY HOMOLOGATION OF STEEL COMPONENTS CONSIDERING BIAXIAL FATIGUE RELIABILITY PREDICTION MODELS

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Abstract. *Product development tools have been extensively used to accelerate the final homologations and release launch with required reliability in order to minimize risks of damages for society and industry. This work explores a project context for a suspension structural component with high safety requirements in an objective manner, proposing a systematic lean planning approach, considering the value added technical deliverables, using available engineering tools from best architecture definition throughout the detailing design, prototype and testing phases. Aiming an earlier release for final manufacturing tools production compared to traditional development methods, a selection of deliverables from modeling, simulation and testing for technological, manufacturing and economics purposes was conducted to find the main crucial information to be part of a decision making process that involves a high amount of monetary value. For speeding release, proposals were explored for accessing the structural integrity of a new component considering materials selection, influence of manufacturing in the mechanical properties, characterization and fatigue testing on samples subjected to measured service loads. The methodology was validated with data from similar component evaluation and the reliability for the new product could be proved by dismissing additional on-road durability tests.*

Keywords*:* *product development; structural reliability; signal analysis; fatigue of materials; accelerated experiments*

1. INTRODUCTION

Structural components development has been accelerated in the past twenty years by using computer simulation tools and fatigue life prediction approaches (Chu, 1997). Engineers have been exploring modeling techniques to considering the uncertainties with safety factors on the design phase to overcome the complexity of conducting sophisticated analysis and experiments that are rarely usable during a high pressure environment for product development.

A lean methodology is proposed based on product development process from Rozenfeld *et al* (2006), using the Stage Gates methodology from Cooper (2001) and the optimization cycles during the design phase. The aim was to improve the maturity of the design and minimize testing efforts over a full hardware or component test bench.

Testing acceptance is currently conducted on manufactured components subjected to a specific service condition or with an accelerated testing program over a full test bench for final structural integrity homologation.

An important input data for damage modeling are the component material properties. In particular the determination of cyclic fatigue properties of the final manufactured parts is recommended to reduce uncertainties as it enables the use of parameters considering the hardening effects caused by the production process (Narderi *et al*, 2011).

Fatigue cracks are mostly initiated on components surface where plane stress fatigue methods can be adopted (Draper, 2008). Therefore, significant efforts on mathematical modeling development have been made considering the bi-axial damage behavior (Brown and Miller, 1973). Multiaxial stress environment can be proportional or non-proportional even under uniaxial loads due to geometry constrains at notches (Fatemi and Shamsaei, 2011). Non proportional stresses require often the critical plane approach (Chu, 1997) and the range acceptance criteria can be used to simplify the analysis scope for proportional loading (Brown and Miller, 1973).

The success of a multiaxial fatigue prediction is directly influenced by the ability to acquire accurate strain time histories (Chu, 1997). Efforts must be made to find the critical stress regions for detailed and precise investigation, instead of a generalized fatigue approach. Therefore, discovering the high stress positions on a given component is a must for setting the strain gages over the critical damage locations for signal acquisition.

Whenever possible it is imperative to search for alternatives that consider consolidated uniaxial fatigue models due to results correlation robustness (Manson and Halford, 2006). A simplified approach would be the generation of an equivalent load histogram from a multidirectional stress field that could be handled by the well established uniaxial fatigue models (Macha and Nieslony, 2012). With the local strain approach been the most indicated for durability prediction by fatigue damage calculations in the automotive industry (Conle and Chu, 1997), creating a reliable model for equivalent strain time history is important for calculating the component total life expectancy with confidence.

For final structural homologation purpose, manipulation methods for accelerate tests results considers 1) Associated to a cycle testing frequency increase up to the resonance limit, the actual praxis includes manipulation of input data by ignoring the low range cycles below 15% of the maximum load (Heuler and Seeger, 1996), 2) building up a cumulative distribution from a time-history rainflow (Grubisic, 1996) or 3) filtering the measured events with calculated stresses below 50% of the material fatigue limit (Narderi *et al*, 2011). A successful technique was proposed using the strain amplitude together with the Smith-Watson-Topper fatigue model (Smith, Watson and Topper, 1970) for editing the cycles with the highest associated damage (Stephens, Dindingert and Gunger, 1977), reducing considerably the signal length and consequently the time to run a complete test program.

The sophisticated testing facilities used for simulating complex mechanical system often found in road vehicles, under a multiaxial loading environment could be reduced to a simple uniaxial material sample validation by considering the fatigue phenomena localized on the component material region subjected to the measured strain environment. This approach showed to be promising for accessing the required experimental results for final development release.

This paper describes a methodology proposal and mathematical modeling for setting a development approach considering the maturity enhancement from concept creation, setting the design specification based on reliability tools and benchmarking, and experimental approval using the bi-axial fatigue theory and manufactured components material properties for damage calculation, as well as generating an uniaxial equivalent signal from a complex plane strain measurements to be used as input for a specimen fatigue testing under variable loading condition. Three designs are considered as a study of case: two of them are existing ones with reference structural and performance data available and a third is a new development that has followed the proposed technique.

2. LEAN METHODOLOGY BASED ON KNOWLEDGE

The development goal was the creation of a new suspension component (NSC), based on the structural performance of an existing part used in severe application (SSC), that could be interchangeable with another existing design currently used in a lighter application (LSC), with time and costs restrictions.

A new method for developing structural components was created for accomplishing the time and costs constrains using more engineering analysis rather that extensive on-road testing procedures. From numerical simulation to component material testing, this work concentrates the efforts on data manipulation and critical approach to set the maturity risks for the new design as a pilot to be further used in similar development cases.

The project scope follows the main deliverables workflow for accomplishing the full development program as presented in Fig. 1. After defining the concept based on functional requirements, the design phase begins already with a well selected architecture and is than subjected to reliability and engineering tools in a cycle based procedure to achieve the best solution considering technical performance, manufacturing needs and optimization over critical parameters such as weight and stiffness. Than, a theoretical stress analysis using the Finite Element Method was done for searching the critical regions that will guide the strain-gages positions. After, measurements over a reference test track were accomplished and subsequently signal analysis conducted for checking data statistics and proportionality. The materials fatigue properties were later obtained from specimens of manufactured parts using the E606-04 procedure. The fatigue damage model calculation was done considering the rainflow cycle counting technique, Brown-Miller and Ramberg-Osgood equations (Draper, 2011) associated with the principal strain from the measured data, and the Palmgren-Miner (Draper, 2011) method for cumulative damage results. At this point, an equivalent strain signal was generated by extracting the rainflow cycles that actually cause damage, which was transformed in a load input signal using the Ramber-Osgood model, enabling a load controlled material durability experiment. Finally, material specimens from the three manufactured components were tested and the results plotted in a Weibull diagram (Stephens *et al*, 2001), which were than compared with actual field data from the two reference parts.

The lean based process had considered the Stage Gate methodology from Cooper (2001) for the complete design, selection of the most appropriate engineering tools to be applied at each phase for minimizing technical risks and setting maturity levels for early decisions. In order to accomplish the deliverables with quality, engineering training and expertise acquisition were considered during each step by setting the future requirements and establishing an information workflow throughout the project team.

In traditional project process, deliverables are provided by different areas in a sequenced form so managerial communication is impaired. In this model, a group does the work and makes decisions, and then communicates the delivery for subsequent area. This creates a waste of time problem, lack of understanding, and a weak commitment to past decisions (Clausing, 1993). Furthermore, critical decisions are only taken in an early step of the project generating a lot of conflicts (Womack et al., 1992). These disadvantages can be overcome by applying the practice of simultaneous development, when investment decisions can be taken at an early stage because members are working together, have information about the status of project progress and can thus take risks (Womack et al, 1992). The application of concurrent development based on multidisciplinary teams, independent of the form of leadership and project structure in the company and should therefore be encouraged to bring information and participation of everyone involved.

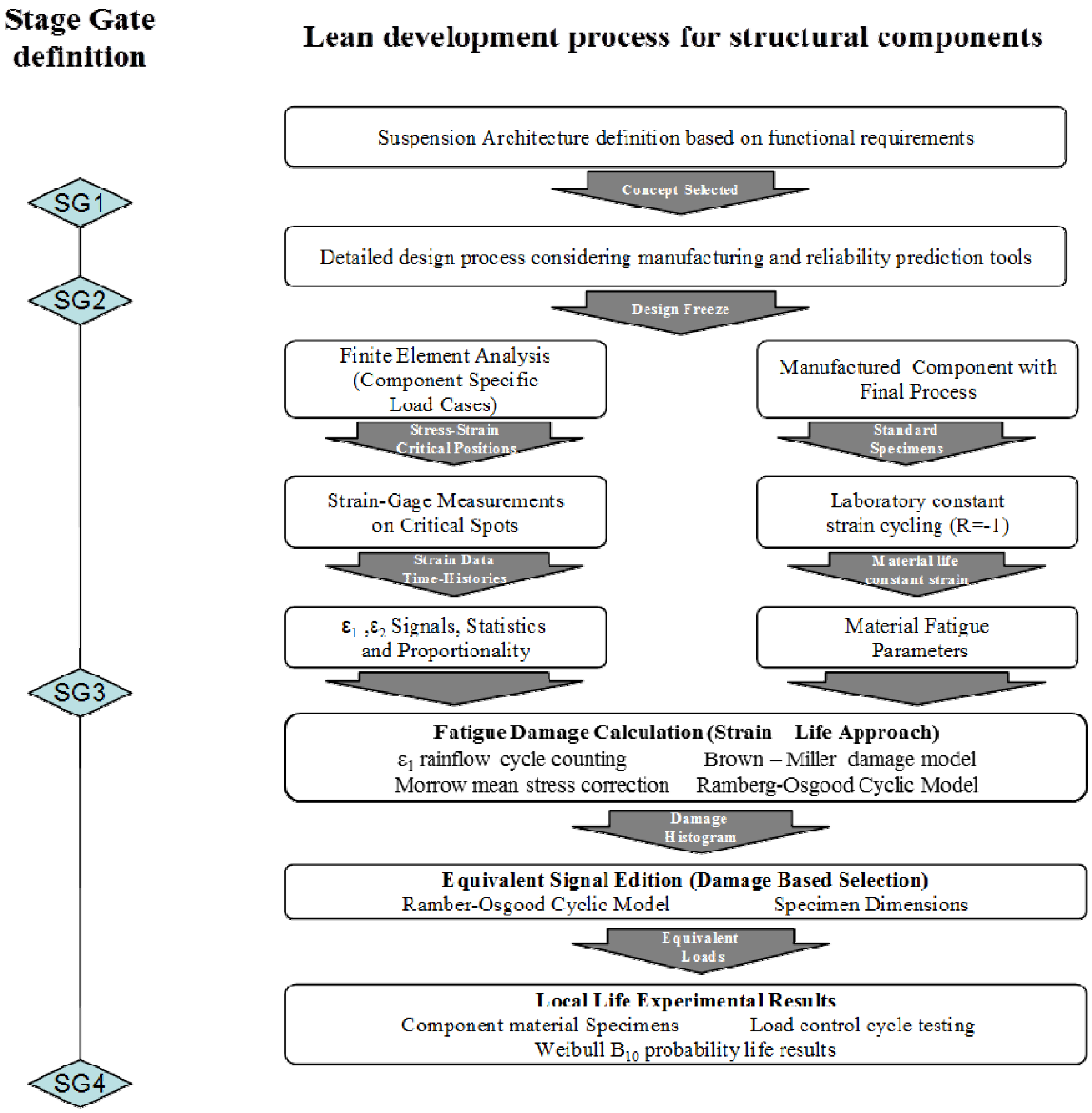


Figure 1. Proposed methodology workflow

3. CONCEPT PHASE (SG1)

3.1 Vehicle suspension architecture

A vehicle suspension system's main function is to absorb the vibrations coming from the floor, and so act as a system to modify the transmission dynamics of the accelerations generated by the irregularities of the ground. The suspension system under study comprises a concept applied to the rear axle for passenger vehicles with pneumatic feature. Figure 2 shows the concept for this type of suspension with four air bags (1), the driving axles (2), four shock absorbers (3), two supporting beams (4), two stoppers (5) and two lower bars and parallel upper "V" bars (6).

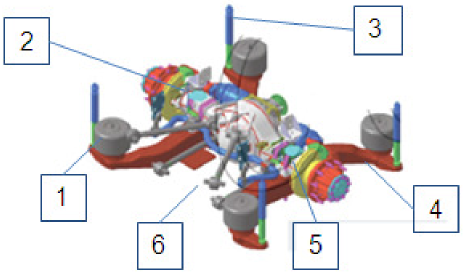


Figure 2. Suspension Architecture

3.2 Concept selection using Computer Aided Tools for Design (CAD) and Engineering (CAE)

The first evaluations were performed in CAD to check the kinematic behavior of the interface suspension / vehicle . On the lateral behavior it can be observed in Fig. 3 a significant difference in the roll angles for the two proposals in study: stoppers over the axle or inside the bellows. This signaled a risk that the version with stoppers over the axle could present an undesired excessive roll-behavior in curves compared to the than stoppers inside the air bellows concept.

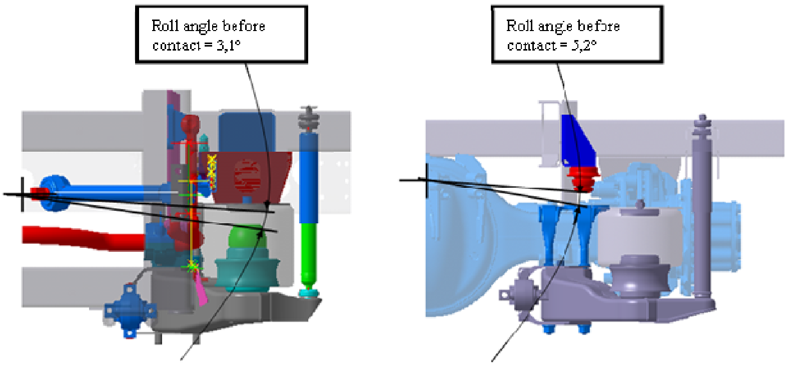


Figure 3. Vehicle lateral kinematics from CAD kinematic analysis

As CAD tool does not provide performance data for the suspension system, therefore a comparative analysis of the dynamic behavior of the vehicle side is recommended to finally understand the effect of the placement of stoppers. As checked before, this placement may compromise dynamic performance and therefore non-compliance with requirements.

The complete vehicle was modeled using the multibody technique (MBS) in the Simpack ® commercial program, which considers the suspended and unsprung masses as well as the geometry and joints between the components of the front suspension and rear respectively, as well as the stiffness and damping curves related to the air bellows and shock absorbers. There were imputed two simulations lateral load cases by applying gradients of lateral acceleration: in a circle trajectory and lane change maneuver at 60 km / h. Results from Fig. 4 shows that the version with stoppers inside the air bellows presents stiffer performance and therefore lower body lateral acceleration.

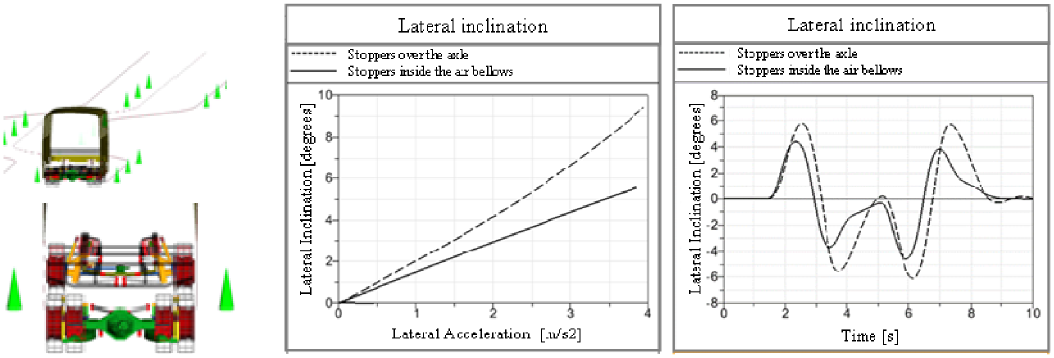


Figure 4. Vehicle lateral behavior from CAE multibody analysis

The selected concept with the stoppers inside the air bellows defines the best solution for the suspension system concerning driving behavior. The goal now is to define the main components in order to cope with the expected loads from this configuration. A main element of the system is the suspension beam that carries the body and receives the loads from the ground through the axles. Three different designs are in context and will be investigated from its durability performance. Two already exist with data from the field and a new one defined as been necessary for this concept definition will be the object of the study from this point.

4. DESIGN PHASE (SG2)

4.1 Benchmark data acquisition

The two existing designs presents at this point subjective specifications leading to uncertainties while taking different parameters as benchmark before a quantitative evaluation. The main aspects under analysis would be the weight and the structural performance within the defined concept from the phase before. The severe application suspensions component (SSC) is already used into a system with the stoppers in the air bellows with success, but does not attend the interchangeability requirements and is heavier that the light application suspension component (LSC) that is applied in a system with stoppers over the axle and attend the modularity and weight requirements.

Thus objective data was required and a measurement procedure for weight and structural performance was initiated for setting the targets for the new suspension component (NSC).

The weight measurements from Fig. 5 show that a target of 68kg would be required as benchmark for the new component NSC.

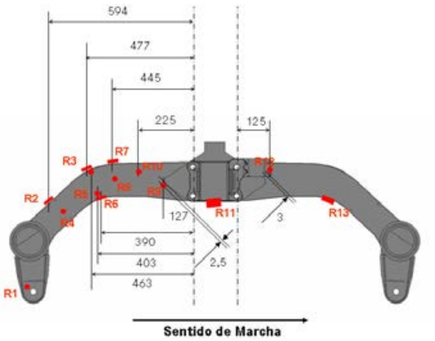
(a) SSC – **73,4 kg***   (b) LSC = **67,9 kg**

Figure 5. Weight comparisons after measurements

The strain measurements with the defined architecture was also conducted adapting both beams in a same vehicle and riding over a specific torture track used for accelerated durability approval, which is the homologation criteria for structural performance defined for this work as well. The strain-gages were positioned in specific points from former Finite Element Analysis (FEA) and checked for its structural performance by comparing the results only with a yield strength criteria. Table 1 presents the strain gages over the yield strength in red for the SSC and LSC respectively.

Table 1. Strain measurement transformed in von Mises stress [MPa]

	Load = 13t	
Strain Gages	Stopper inside Air Bellows	
	SSC	LSC
R1	**Plastic**	187
R2	341	256
R3	208	**Plastic**
R4	**Plastic**	**Plastic**
R5	**Plastic**	**Plastic**
R6	**Plastic**	**Plastic**
R7	166	**Plastic**
R8	238	**Plastic**
R9	290	**Plastic**
R10	**Plastic**	**Plastic**
R11	**Plastic**	**Plastic**
R12	**Plastic**	**Plastic**
R13	**Plastic**	**Plastic**

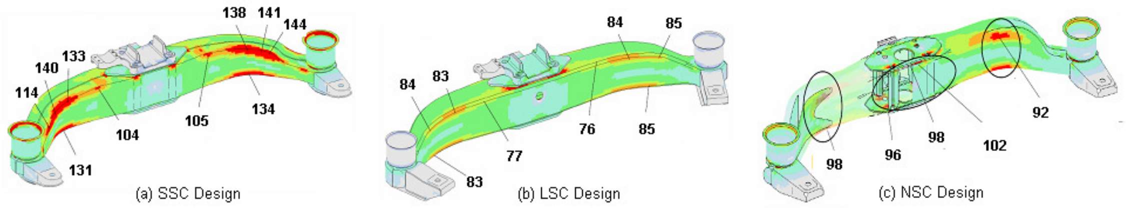


As the SSC is the current benchmark regarding structural performance and the LSC presents stresses above the yield strength in several spots, a new design is justified. Detailed strain data fatigue analysis will be conducted on the testing phase to establish damage correlation between the NSC and the SSC for precise correlation in the plastic zone.

4.2 Finite Element Analysis (FEA)

The Finite Element Method (FEM) is a well known engineering tool for predicting the structural stresses of a component geometry subjected to loads and guided by constrains. This analytical method divides the continuum in small elements, linked by nodes, that represents the elastic equations for determining the node displacements and the material properties for calculating the corresponding stresses at each element position.

The three components under investigation are different rear axle carriers commonly used in commercial vehicles air suspension type. Figure 6 shows the FEM results based on a non-linear static analysis for the vertical stiffness elements concerning the rubber bushings stoppers modeling and contact with upper brackets. The solver used was Permas® and the meshing was done mostly using two-dimensional quadratic elements acknowledging to the corresponding sheet thickness and manufactured materials. The models for the (a) SSC Design, (b) LSC Design, (c) NSC Design were submitted to an impulse load case of 2,5G vertical acceleration downwards over the whole vehicle mass considering the rear axle carrying a 13 t payload (1,7 t unsprung mass plus 11,3 t sprung mass).



(a) SSC Design

(b) LSC Design

(c) NSC Design

		E380TM	St52	LNE700
Su	[MPa]	541	428	766
Se (0,2%)	[MPa]	454	324	430

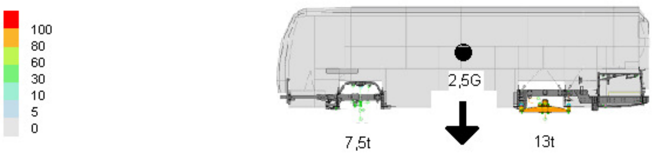


Figure 6. FEM results for the three designs as percentage of the respective material yield strength.

The results are presented as a percentage value based on the material yield strength criteria - Se (0.2%) - as specified for SSC – E380TM, LSC - St52 and a new proposed material for NSC - LNE700. The LSC design presented stresses above the criteria in a bigger area forecasting plastic deformation during service loads. The NSC design presented the level and contour plots below criteria as the benchmark values from SSC design.

From this static analysis it was possible to define the critical areas which were assumed as been the strain-gages position for time-history measurements, already accomplished for the SSC and LSC, and than a refined fatigue analysis. At this maturity level, it is possible to conclude that the new design complies theoretically with the reference SSC design in a quasi-static environment.

4.3 Manufacturing process

As part of the investigation, the manufacturing process was carried out in conjunction with the nominated supplier. A study of the concept for a hot forming in the two main half was done, considering the plate into the press at 800^{o}C. From there, four stages of operation were developed and simulated as shown in Fig 7.

This simulation shows that there will be no split on the sheet metal part and the position with decrease on thickness will not compromise the stress requirements rising from the prior structural FEM analysis. Therefore the concept was approved to be detailed.

The design and manufacturing maturity presented in the design phase demonstrated that it was possible to assume a definitive tooling for the two half instead of a soft tool for testing and later the final tool. This decision making using information coming from well modeled engineering simulation playing an important role in the lean process enabling considerable time and cost savings throughout the project so far.

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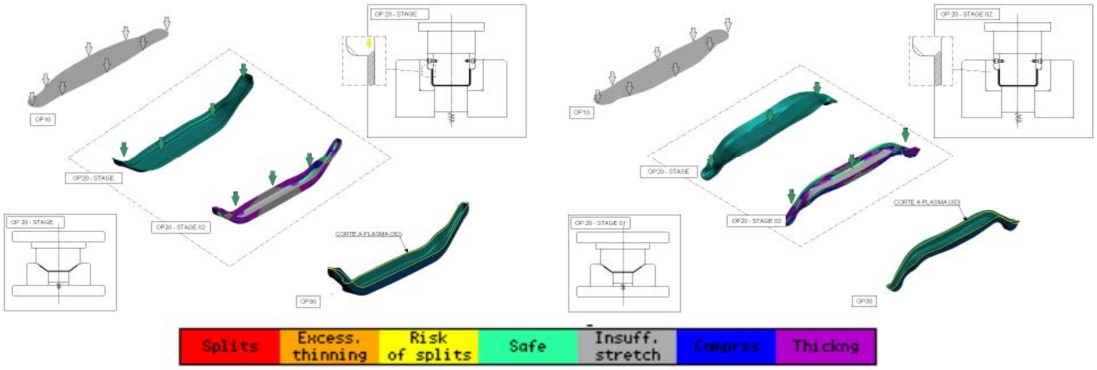


Figure 7. FEM stamping results for the four stages assumed in the production concept

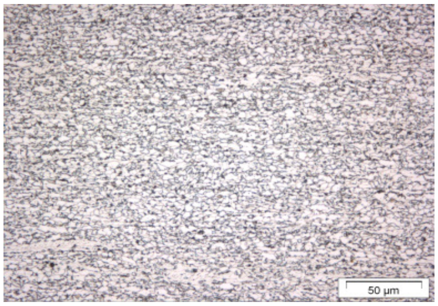
5. PROTOTYPE PHASE

5.1 Manufacturing design and prototypes

Manufacturing design was conducted based on the approved concept. All forming process of NSC component was prepared for a hot stamping above 800^o in the first stage. Concern was the material cooling rate during the operation and consequences to the final microstructure. Table 2 below presents the temperature change over each punch step and the final microstructure showed fine grains as a normalizing process.

Table 2. Cooling rate and final microstructure for the NSC component.

Punch Stage	Temperature [oC]	Time [s]
First	850	5
Second	740	8
Third	660	8
Fourth	550	8
Cooling	Ar	-



5.2 Materials data

Precise materials data are important for fatigue life calculation. Whenever possible, a manufactured material sample shall be used for determinate the real properties. Therefore, extraction of specimen directly from the components would inherit the manufacturing effects on the microstructure and give more accurate cyclic fatigue parameters to be used furthermore on the life prediction model. The Fig. 7 shows how the specimens were removed from manufactured parts, as well as their dimension and geometry.

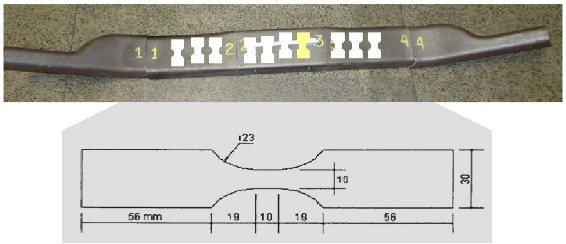


Figure 8. Geometry and dimensions [mm] of the specimens taken from manufactured parts.

The low cycles fatigue constants values for the three steels are presented in Table 3 and were obtained following the ASTM E606 – 04 standards. The tests were carried out in fully reversed strain control in air and at room temperature using a computer controlled 100 kN MTS Landmark closed-loop servo-hydraulic testing machine. A sinusoidal strain waveform was applied with strain ratio of R_ε= -1 at fixed frequencies with values ranging from 0.5 Hz to 3.0 Hz.

Table 3. Low-cycle fatigue constants for the materials

Material	n'	K'	b	σ'f (MPa)	ε'f	c	E [Mpa]
E380TM	0,0754	588	-0,0695	702	0,269	-0,5653	189000
St52	0,1737	812	-0,1132	827	0,31	-0,5335	210000
LNE700	0,0872	799	-0,085	967	2,27	-0,8	195000

The strain-life curves were presented for the materials in Figure 9 applying the Coffin-Manson fatigue-life relationship, Eq.(1) (Draper, 2006). The results presented demonstrate higher lives for the low-cycle fatigue region for the LNE700 steel while for high cycle fatigue region the behavior is very similar to the E380TM and St52. It can be seen that the St52 steel exhibits low and high cycles regions very close to that presented by E380TM steel.

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f^{'}}{E}(2N_f)^b + \varepsilon_f^{'}(2N_f)^c \qquad (1)$$

In the Eq.(1) the variables are: Δε= true strain range, $2N_f$ = reversals to failure; and the constants are: σ'_f = fatigue strength coefficient, E = Young's modulus, b = fatigue strength exponent, ε'_f = fatigue ductility coefficient, c = fatigue ductility exponent, n´= cyclic strain hardening exponent and K´= cyclic strength coefficient.

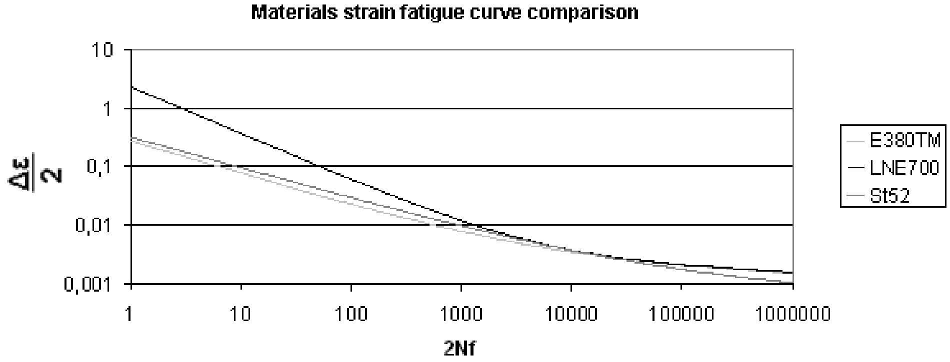


Figure 9. Experimental strain-life curves obtained for the materials

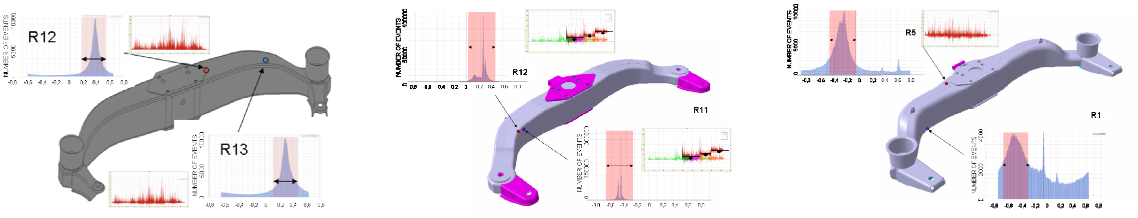
6. TESTING PHASE

6.1 Strain data acquisition and manipulation

Based on the FEA results, the existing SSC and LSC designs were instrumented, assembled and measured on a vehicle for one lap over a standardized test track, while the NSC design prototype was waiting for the tool manufacturing which was released after decision based on the structural benchmark correlation for the peak measured stresses and the FEM static stress results from previous analysis. Next, the experimental procedure was conducted for strain time-history acquisition in a similar procedure on the NSC design prototypes parts.

The strain-gages were positioned following the FEM critical spots for measurements and the acquired time-histories for ε_x, ε_y and ε_{45} were transformed into principal strains. The LSC design data required further manipulation due to some local plastic deformation and the residual strains were eliminated by subtracting the deformation value from the original signals. The measurement points with higher RMS values were assumed to be detailed for its proportionality. The signals proportionality were calculated by Eq. (2) and are presented in Fig. 10 for (a) SSC design, (b) LSC design, (c) NSC design.

$$\phi = \frac{1}{2}\arctan\left(\frac{2\varepsilon_{45} - \varepsilon_x - \varepsilon_y}{\varepsilon_x - \varepsilon_y}\right) \tag{2}$$



(a) SSC Design (b) LSC Design (c) NSC Design

Figure 10. Highest measured RMS strain values positions and signal proportionality

Most of the measured time-histories lies within the 10^o proportional range, with exception of the NSC design point R5. Therefore for the critical evaluation points, the precision of results would be minor affected in 2% for a fatigue analysis considering the Brown-Miller model (Brown and Miller, 1976).

6.2 Local strain fatigue analysis

At this stage, all strain time-history and materials properties are available for conducting a fatigue damage analysis. Considering the time-history data proportional, the bi-axial fatigue from Brown-Miller suggested Eq. (3) could be solved without requiring the critical plane approach, what simplifies the analysis by reducing engineering and computational efforts.

$$\frac{\Delta\gamma_{\max}}{2} + \frac{\Delta\sigma_N}{2} = 1.65\frac{\sigma_f^{'}}{E}(2N_f)^b + 1.75\varepsilon_f^{'}(2N_f)^c \tag{3}$$

Another equation commonly used, Eq. (4), proposes that the initial crack will initiate on the plane that experiments the highest principal strain amplitude and is recommended for high strength metals (DRAPER, 2006).

$$\frac{\Delta\varepsilon_1}{2} = \frac{\sigma_f^{'}}{E}(2N_f)^b + \varepsilon_f^{'}(2N_f)^c \tag{4}$$

Both equations can be combined by multiplying the Eq. (4) by a factor of 1.7 and creating an approximated Brown-Miller equation in terms of the principal strain data as shown in Eq. (5) what would be recommended for ductile materials as well. The measured time-history can be easily transformed in terms of principal strain as input for the modified Brown-Miller Eq. (5).

$$1{,}7\frac{\Delta\varepsilon_1}{2} \cong 1{,}65\frac{\sigma_f^{'}}{E}(2N_f)^b + 1{,}75\varepsilon_f^{'}(2N_f)^c \tag{5}$$

In order to consider the mean stress effect on the fatigue damage, the Morrow correction (Morrow, 1968) was adopted, as it is more indicated for steels while the Smith-Watson-Topper would be more indicated for castings and aluminum (Dowling , 2007). The final equation 6 is to be used for the proposed method.

$$1{,}7\frac{\Delta\varepsilon_1}{2} \approx 1{,}65\frac{\sigma_f^{'} - \sigma_m}{E}(2N_f)^b + 1{,}75\varepsilon_f^{'}(2N_f)^c \tag{6}$$

Another important model extensively used is the Ramberg-Osgood, Eq. (7), which is applied for finding the σ_m (Spinelli, 2012) and later to transform the strain into stress using the cyclic fatigue material data found for the components steel.

$$\frac{\Delta\varepsilon}{2}=\frac{\Delta\varepsilon_e}{2}+\frac{\Delta\varepsilon_p}{2}=\frac{\Delta\sigma}{2E}+\left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \quad (7)$$

The fatigue damage calculation was conducted applying the VBA (Visual Basic Algorithm) routine written matching the algorithm presented in Figure 11 (Spinelli, 2012). First the rosette data is manipulated for principal strains output, followed by classical peak and valley extraction for reducing computational efforts. The simplified principal strains are than submitted to a rainflow cycle counting according to the ASTM E1049- 85 (R2011) standard. Materials fatigue data are inputted into the program. Damage for the input signal is calculated using the Palmgren-Miner cumulative damage method.

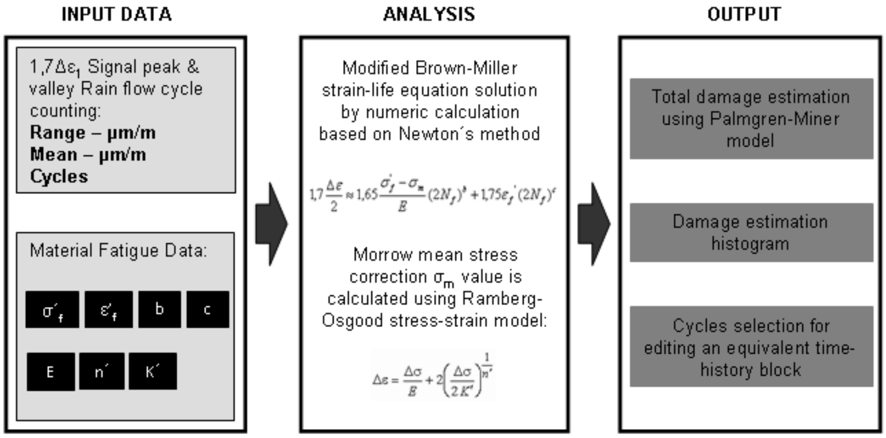


Figure 11. Program algorithm for VBA implementation

The results for the three design and correspondents materials are tabulated on Table 4 as function of the number of laps expected to be accomplished before fatigue failure.

Table 4. Fatigue calculation life results for the three designs as function of number of laps to fail.

	ST52	E380TM	LNE700
LSC design	666		
SSC design		43103	
NSC design			48402

The on-road approval criterion is 3000 laps without failure. Therefore, both SSC design and NSC design would be approved, while the LSC design would be reproved for the required application.

The results correlates with the latest vehicle test data. The reference SSC design demonstrated no failure after accomplishing the approval criteria over five different vehicle test, while failure took place on the LSC design after 929 running laps, as shown in Figure 12. The fracture occurred exactly on the position forecasted by the FEM analysis and where the strain-life calculation presented the highest damage result.

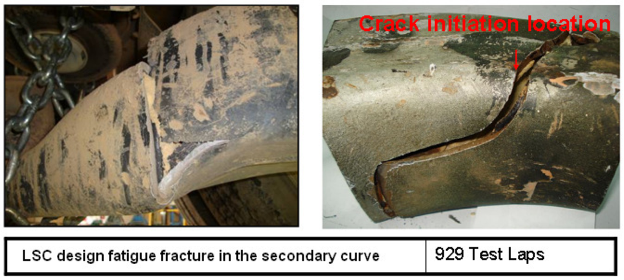


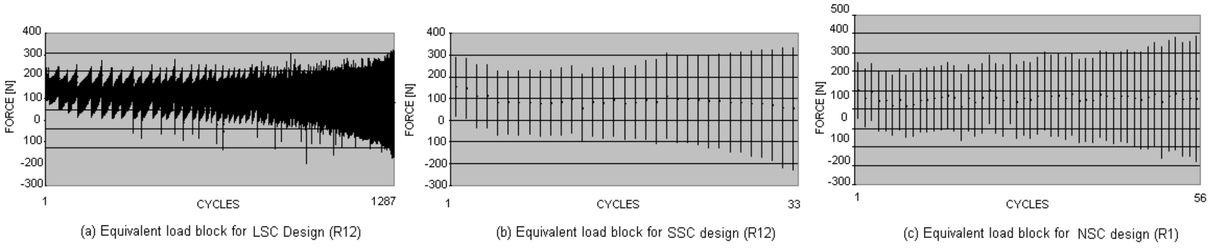
Figure 12. Fatigue failure event during the standard durability track testing program>

The method and modeling demonstrated high confidence for editing equivalent signals considering the cycles in the rainflow counting that resulted in high damage to the material. By separating these cycles, all other cycles that do not influence fatigue are dismissed. The proposed editing method is highly dependent on the material properties as it uses the fatigue damage model from Eqs.(5) and (6) from Ramberg-Osgood for strain – stress transformation.

6.3 Testing program and reliability analysis

Wöhler considered that engineers must have the knowledge of the loads in order to design against fatigue (Shutz, 1996). Therefore load control is the simplest way to check for fatigue performance on a real test as it does not have to account the non-linearity from the material curves, as well as it can be cycled in much higher frequency compared to a strain controlled test program.

The input data for the edited equivalent damage load signals are plotted in Figure 13. It shows a smaller load input signal for designs 1 and 3. For the LSC design, as it suffers damage from a bigger rainflow cycle matrix, the force input signal required resulted to be longer.



(a) Equivalent load block for LSC Design (R12)
(b) Equivalent load block for SSC design (R12)
(c) Equivalent load block for NSC design (R1)

Figure 13. Equivalent load blocks for the three designs of fatigue spectra

At least seven specimens from each components material were submitted to the uniaxial equivalent load time-history in a standard fatigue test device as shown in Figure 14. The testing frequency reached up to 50Hz what enabled to gather the durability cycles results quite fast.

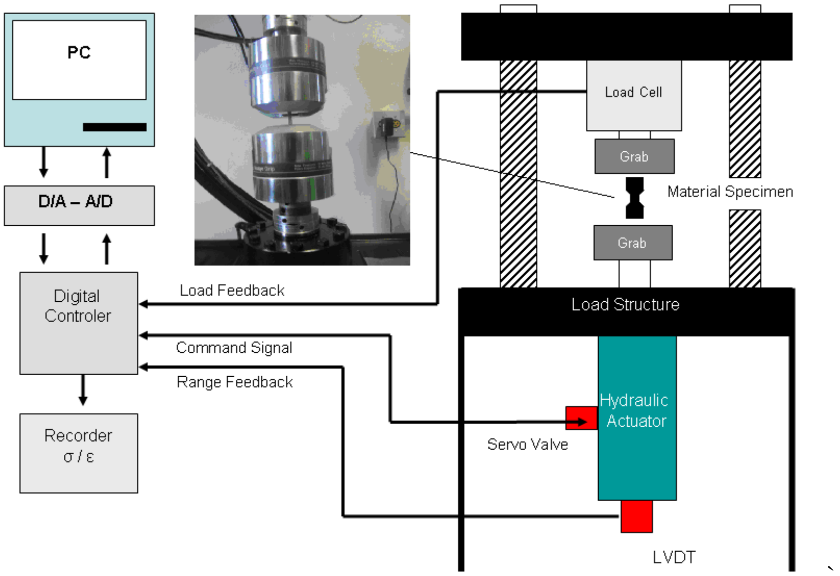


Figure 14. Uniaxial fatigue testing equipment

The results for all specimens were saved and organized on Table 5 as a function of the number of laps from the standard testing track, where one equivalent signal block represents two times the time history of one lap.

Since the results are different for each specimen, Weibull distribution is used as preference for probability fatigue failure analysis (Stephens, 2001). The B_{10} life is an expected value corresponding to a failure rate of 10% which is used to guide engineers for decision. Ranking the experimental data it is possible to find the Weibull parameters for each experiment and plot them all in a diagram presented on Figure 15.

The B_{10} life for LSC design presents good correlation comparing with the reported failure laps from Figure 15 and the fatigue damage calculation prediction from Table 4. From the Table 4 the SSC and NSC designs presented more conservative results in respect to the fatigue damage calculation. Nevertheless, considering the approval criteria of 3000 laps, the testing results demonstrated a positive no-failure experience for the SSC *design*, which can be used as benchmark to structurally release the NSC design for series production. The close relationship from the experimental and theoretical life results validated the method for further applications.

Table 5. Experimental life results for the designs materials specimens as equivalent laps.

LSC design		**SSC design**		**NSC design**	
Sample	**Equivalent Laps**	**Sample**	**Equivalent Laps**	**Sample**	**Equivalent Laps**
BI1 - T	1748	BN1 - T	26250	BG1 - T	43004
BI2 - T	1212	BN2 - T	31534	BG2 - T	19388
BI3 - T	1212	BN3 - T	23156	BG3 - T	19912
BI4 - T	1484	BN4 - T	21382	BG4 - T	32102
BI5 - T	1214	BN5 - T	15378	BG5 - T	31308
BI6 - T	1108	BN6 - T	18488	BG6 - T	93190
BI7 - T	946	BN7 - T	43180	BG7 - T	79230

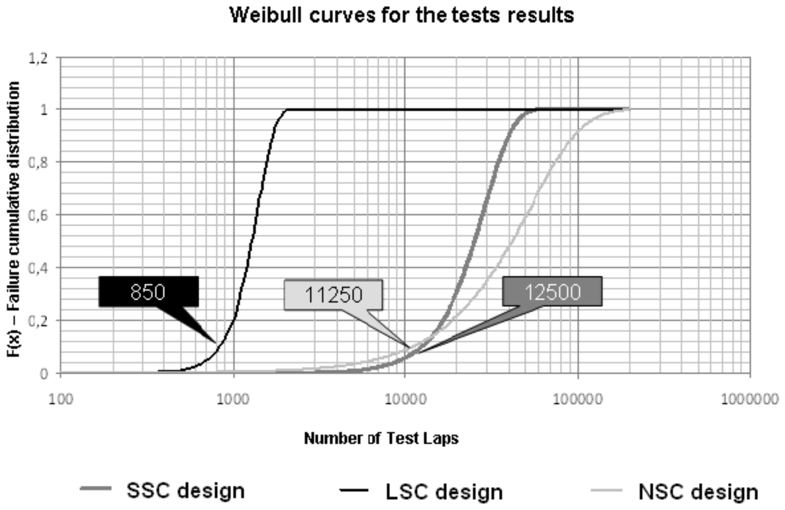


Figure 15. Weibull curves showing the expected B10 life for each design.

7. CONCLUSIONS

The methods employed in this work presented a successful systematic approach for product development of steel components considering the most available engineering tools used in the structural field. From digital to experimental procedures it was possible to set the maturity level for the NSC design allowing an early stage decision making considering tooling investments release and design homologation for production. This structural approach is a differential to be extensively applied and further enhanced for product development processes within a high pressure time to market environment.

The calculation procedure for obtaining an edited equivalent uniaxial load collective together with a simplified material fatigue experiment demonstrated also good correlation with the reference fatigue data, thus, validating this technique for future applications during the testing phase.

The new development named NSC design has reached the desired fatigue life when compared to the successful SSC design. It was released for serial production with high confidence avoiding time consuming on-road durability tests and high costs test bench program procedures.

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