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DESIGN & VALIDATION METHODOLOGY FROM A LIFE PREDICTION PERSPECTIVE FOR THE STRUCTURAL COMPONENTS OF A RECREATIONAL PRODUCT

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Abstract

The paper outlines a design process flow diagram (methodology) that highlights the challenges of engineering design and allows both engineers and students to focus on the development of a creative, effective and profitable solution to meet particular life objective and additional criteria. A case study related to a recreational vehicle is also presented to validate the methodology.

Therefore, to reach the objective of weight reduction for the structural subsystem in a hybrid roadster project, a methodology that allows the optimization of the design parameters according to several types of design criteria has been developed.

Keywords: design and validation methodology; engineering design; design criteria

Intoduction

The particular framework described in this paper is developed because it bears the potential to satisfy two objectives of engineering design: to ensure consideration of each element necessary for a successful design and to ensure that all the consequences of the application of the designed device or process throughout its lifetime are anticipated and examined (Jones and Ertas, 1993).

Incidentally, it is critically important to understand the competition and the trends before any new technology introduction into the market (Otto and Wood, 2001).

The optimization process allows finding one or more combinations of parameters maximizing or minimizing a given design criterion, while the validation activities provide feedback to the designers in order to verify the calculations accuracy and the fulfillment of all design criteria (Iorga and Desrochers, 2011). The authors who laid the bases of the non-linear optimization methods dedicated to the design of structural products are Wilde in 1967, Fox in 1971, Haug and Arora in 1979, Morris in 1982, Ravindran and Reklaitis in 1983, Vanderplaats in 1984, Papalambros and Wilde in 1988. Hence, optimization has been developed and applied in both academic and industrial fields for the last decades to improve products (Papalambros and Wilde, 1988). Now, the challenge is how to imbed these techniques in the Product Design Process (PDP), and to increase their utilization so that the final product fulfills all design criteria and client needs. Research into design methodologies is motivated by the existing gap between analysis capability and optimization capability in structural product design, which was pointed out by Papalambros. The reason for this gap can be understood better if the quantities that determine the optimization capability of the various methods currently employed are considered (Papalambros, 1994): mathematical programming, multi-objective programming, discretized optimality criteria, continuum-based optimality criteria, fully stressed design, finite elements analysis.

An interesting analogy between engineering design validation and medical validation practices is provided by Frey and Dym. In this context, the authors elicit the positive attributes of the validation processes used in medicine although significant gaps still exist in this field (Frey and Dym, 2006). Frey and Wang have developed an "adaptive one-factor-at-a-time experimentation" scheme with the aim to instill improvements in engineering design. The mathematical model and theorems developed by the authors are supported by a case-study from the aeronautical industry (Frey and Wang, 2006).

However, the purpose of this paper is to better organize the use of these methods during the PDP, rather than to provide new design or optimization methods. More specifically, the difference between two paradigms who share similar roots but whose meanings are completely different is worth investigating: method vs. methodology.

Thus, methods are "tools" that are used in making design and to optimize and validate it, whereas methodologies are theories that underpin the engineering decisions about the engineer's range of choices.

In other words, a method is a descriptive approach on how to do something and a methodology is a prescriptive study of the way to do something.

More specifically, considerations will be given to detailed design methodologies that target multiple design criteria and adapt to various design situations (Maropoulos and Ceglarek, 2010; Dym and P. Little, 2009). The detailed design phase in the product development process will also include both the product optimization and the product validation (East and al., 2008; Ertas and al. 1989). The lack of connections between several stages of the product development process (PDP) leads us to search for new approaches in terms of design and validation methodologies, to fill that gap (14-19).

2. DESIGN AND VALIDATION METHODOLOGY

The need to formalize the design and validation process at its detailed phase has been identified in both the industrial and academic fields (Iorga and Desrochers, 2011). Figure 1 shows the steps to follow by the design team from the initial modeling stage of the product up to its final validation phase. The methodology is typically applicable to structural products from the recreational products industry *(frames, handlebars, forks, bumpers, etc.)* for which a detailed study of their service life is required. For illustration purposes, the various steps of the proposed methodology will be applied to the design of a new, lightweight frame (figure 3), for the tricycle shown in figure 2 (Lee, 2005; Lee, 2009 and Choi, 2007).

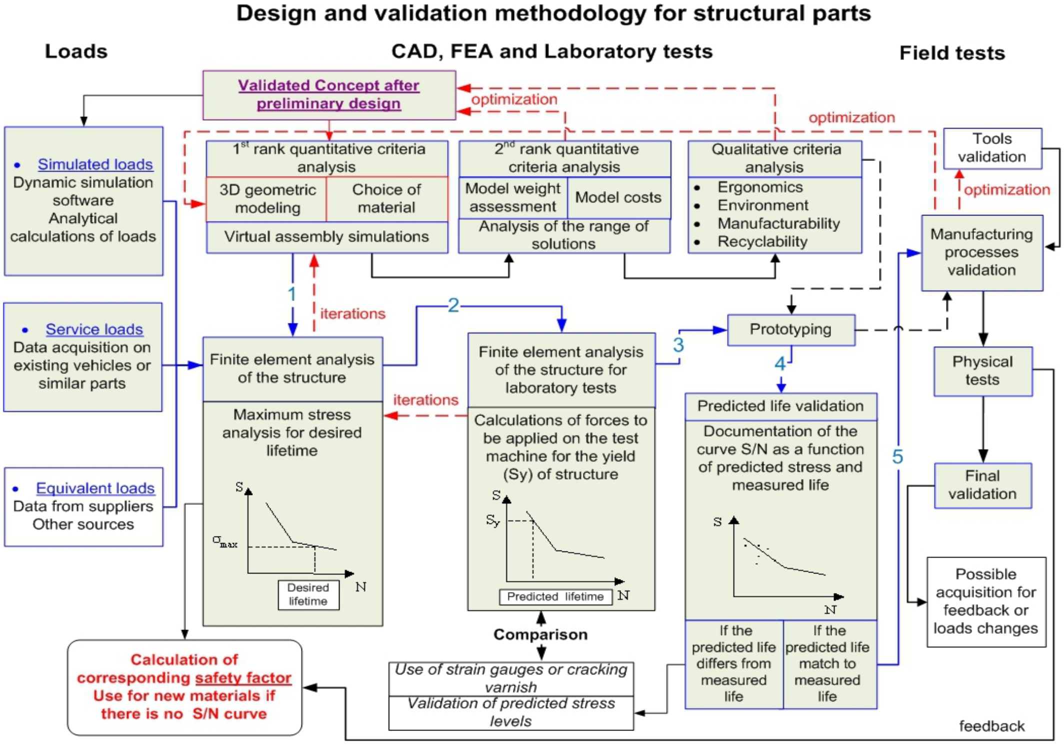

Fig.1: Design and validation methodology for the structural parts of a recreational vehicle [5]

However, it should be noted that the quantitative data used in the remainder of the paper have been roughly estimated and hence, do not accurately represent the reality. Consequently, the authors have no responsibility for the misuse of these data. Using the quantitative data in any other projects could lead to products that do not respect some design criteria.

2.1. LOAD CASES IDENTIFICATION STAGE

As shown in the methodology, there are activities related to the validation process that can be made at the detailed design stage or earlier. For example, several tools for gathering load-cases data can be used before the criteria analysis step. Generally speaking, three types of data acquisition methods have been identified: (1) virtual method *(simulated loads)*, (2) experimental method *(service loads)* and (3) benchmarking methods *(equivalent loads).*

In the way of virtual methods, simulation software may be used to determine the dynamic loads on a product under certain conditions of speed, etc. In parallel, an analytical calculation of the actual loads can also be performed (figure 2).

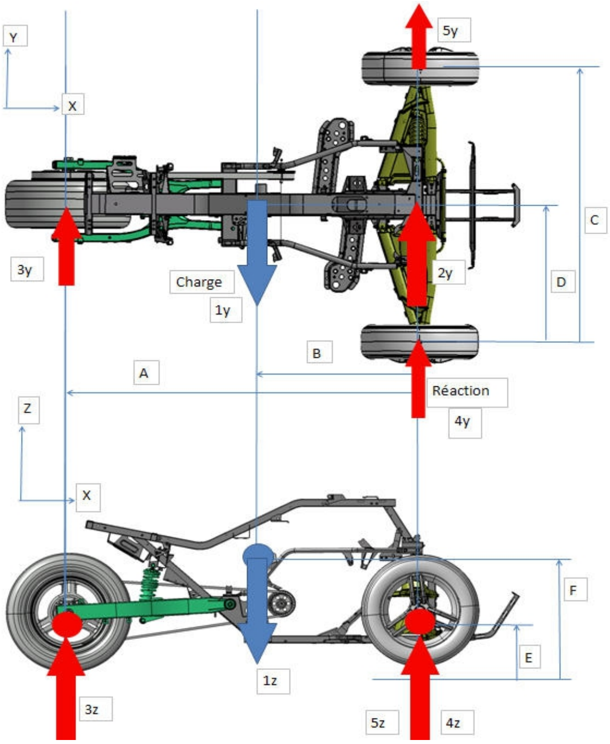

Fig.2: Free-body diagram of the vehicle frame of reference.

For instance, we assume that during a ride a transfer of loads between the front wheels occurs when the pilot turns the handlebar to the left or to the right. Hence, if the pilot attempts a change of direction along a circular path of radius $\mathbf{R_g}$ with a speed $\mathbf{V}$, the rotation of the handlebar will cause the wheels to steer via the steering system. Accordingly, the steering of the front wheels will generate the lateral forces $\mathbf{F_{4y}}$ and $\mathbf{F_{5y}}$ called drift, which give rise to the lateral acceleration γ_t :

$$\gamma_t = \frac{V^2}{R_g}$$

The loads distribution for a typical lateral solicitation *(turning)* is shown in figure 2. Centrifugal force $\mathbf{F_{1y}}$ was decomposed following reactions $\mathbf{F_{3y}}$ and $\mathbf{F_{2y}}$. The transversal force $\mathbf{F_{2y}}$ was also decomposed into $\mathbf{F_{4y}}$ and $\mathbf{F_{5y}}$, due to the effect of transferring loads between the front wheels. The loads calculations were performed for an acceleration of $\gamma_t = 0,5g$.

The results of these analytical calculations of loads are summarized in table 1.

Using the experimental method, data acquisition is made with strain gauges, applied to existing vehicles that have been developed either within the organization or among competitors (Lee and al., 2006). This type of method allows multidisciplinary teams to understand the behavior of the structure under actual load conditions.

Table 1: Typical load cases for a recreational vehicle

Load axis	F1 (N)	F2 (N)	F3 (N)	F4 (N)	F5 (N)
Y	3448	-1817	-1631	-1289	-528
Z	6894	-3633	-3261	-2578	-1055
Turning	**7708**	-4062	**-3647**	**-2882**	**-1180**
Braking	**-**	**-**	**-2160**	**-3720**	**-3720**
Braking + bump	**-**	**-**	**-5000**	**-5236**	**-5236**

To determine the desired lifetime of a product, a spectrum of load cases must first be identified (Joo and al., 2003). Thus, for the vehicle whose frame is depicted in figure 2, the number of cycles for each loading case was established by performing a ride along a 10 km road with several bumps, curves and potholes. Considering that the studied vehicle is seasonal, an estimated service life of 50 000 cycles has been arbitrarily chosen. All data regarding the occurrence of the various load cases were collected on the field and compiled in table 2.

Table 2: Lifetime estimation for a recreational product

Lateral loads **(cycles)**	Braking **(cycles)**	Braking + Bumps **(cycles)**	Covered distance **(Km)**	Lifetime estimation **(Cycles)**
35	25	25	10	85
35000	25000	25000	10000	85000
175000	**125000**	**125000**	50000	425000

Thus, at the end of this step of the product development process (PDP), different load cases are identified and a product lifetime is estimated.

2.2. CRITERIA ANALYSIS STAGE

The data obtained at the load cases identification stage will be used to model, analyze and validate the product with respect to all design criteria: 1st rank quantitative criteria *(structural criteria)*; 2nd rank quantitative criteria *(economic criteria)* and qualitative criteria *(design for X criteria)*.

2.2.1. 1st RANK QUANTITATIVE CRITERIA

As illustrated in figure 1, the analysis of the quantitative criteria of 1st rank represents the earliest activity at this stage of the PDP and its result will be a virtual prototype (DMU). The main activities carried out at this stage are the computer aided modeling of the geometry and the analysis of several candidate materials using finite element simulations. These activities can be carried out iteratively and they aim to analyze the product's ability to withstand the loads identified in the upstream steps.

Hence, for the tricycle example, three frame concepts and one reference frame were modeled and preliminary analysis by finite elements were carried out in the ANSYS environment for each combination of geometry/material to verify their behavior under the action of the load cases identified earlier in the PDP. More specifically, the following combinations of geometry/material have been investigated: planar optimized steel frame (Concept I), planar aluminum frame (Concept II) and *space* aluminum frame (Concept III). Figure 3 illustrates the DMU of Concept I frame which has been designed and analyzed at this stage of the PDP.

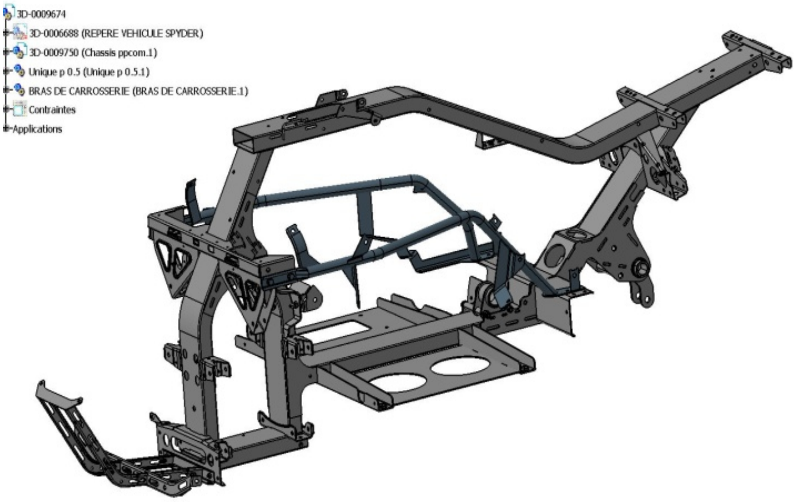

Fig.3: Roadster planar frame concept [14]

Table 3 provides a comparison between the proposed concepts, according to different design criteria: stress, deflection and yield strength based safety factor. Comparison between the safety factor of the reference frame and those of the new concepts shows the extent of the optimization that has been performed at this early step of the PDP.

This step must be completed before beginning the analysis of the quantitative criteria of 2nd rank because the cost analysis or weight determination of a product is not possible without identifying first some solutions combining the two main design variables: the geometry and the material.

Table 3: Functional concepts comparison

Design Criteria	Reference	Concept I	Concept II	Concept III
Stress (MPa):				
Braking	140	150	125	155
Lateral loads	200	250	160	180
Braking + Bumps	170	240	190	145
Safety factor:				
Braking	X	-26,5 %	-31 %	-55,5 %
Lateral loads	X	-26 %	-10,5 %	-19 %
Braking + Bumps	X	-31,5 %	-32 %	-11,5 %
Deflection (mm):				
Braking	2.1	2.6	4.4	2.6
Lateral loads	3.1	6.1	7	9.2
Braking + Bumps	2.9	4.4	6.35	3.7

2.2.2. 2nd RANK QUANTITATIVE CRITERIA

In the second step of the criteria analysis stage, designers are interested in the product's ability to respect other quantitative criteria related to the competitiveness of the product on the market such as its cost, weight or volume. These criteria are closely linked and depend on the product geometry and material choice. Table 4 presents the results of this step of the PDP.

Table 4: Results of economic criteria analysis (Tacher, 2012)

Concepts		**Reference**	**I**	**II**	**III**
Weight		X (kg)	-14 %	-61 %	-73 %
Raw material cost	**Cost/m**	X ($)	-27 %	+8 %	-68 %
	Meters	X (m)	-0 %	-0 %	+155%
	Total cost	X ($)	-27 %	+9 %	-19 %
Processes cost	**Folding**	X ($)	-0 %	+28,5 %	+151%
	Welding	X ($)	-0 %	+32,5 %	+130,5%
Cost difference			-18%	+12%	+37%

Iterations back to the previous steps are also possible and even desirable in some cases to identify more relevant combinations *(geometry/material)* that meet all quantitative criteria *(1st and 2nd rank)*. To determine the profitability of the product, the cost analysis should cover all those activities of the PDP that involve expenditures *(design/validation, manufacturing, maintenance, recycling, transportation, storage, etc.)*.

Thus, an inconclusive result for such an analysis could lead to stop the project or to search for alternatives *(removal of a production chain, outsourcing tasks to suppliers, etc.)*. In our case, the third concept didn't meet the cost criterion in terms of dollars invested per kg saved and consequently, it was discarded (see table 4).

2.2.3. QUALITATIVE CRITERIA

Moreover, a qualitative criteria analysis is imposed at the detailed design phase to verify whether a product meets the non-quantifiable requirements established at the preliminary design phase. Ergonomics, aesthetic and manufacturability are part of this category of design criteria and their analysis will provide designers a feedback on customers' needs and on the conceptual choices made accordingly (Boothroyd, 2002).

Considering that the first concept (steel optimized planar frame) is very similar to the existing frame regarding its assembly, tooling and ”friendliness” toward engine maintenance, the engineering team has decided to develop this concept and to move on to the preliminary steps of the validation stages.

Nonetheless, depending on the customer needs, or product specifications, several iterations may be initiated on the geometry or material of the product, always in line with the quantitative criteria analyzed in the previous steps as well as the qualitative one addressed in this section (Cooper, 1993).

2.3. NUMERICAL VALIDATION

To prove its relevance, the proposed approach was applied to the reference frame which is already on the production line. As a first step of the structural validation of the product, a finite element analysis (FEA1) was performed using the values identified at the load cases evaluation step. After determining the maximum stress that can be supported by the frame while ensuring the desired service life of the product, a second finite element analysis (FEA2) is necessary to simulate the product on a virtual testing machine along with the forces to be applied by the machine onto the frame.

2.3.1. FINITE ELEMENTS ANALYSIS OF THE STRUCTURE WITH THE ACTUAL LOADING CONDITIONS (FEA1)

The properties of the chosen material are used at this step to determine the maximum allowable stress in the critical sections of the product for a desired service life *(see the box «finite element model of the structure»* FEA1*)*. In the case of materials for which no S/N curves are available, a safety factor will be required to account for the estimated service life of the product. An estimated S/N curve for the steel grade was used to aproximate the lifetime of the reference frame. Thus, according to the curve, for a lifetime of 425000 cycles, the maximum stress should not exceed 260 MPa in the critical zones.

After several iterations performed at the FEA1 step, an optimal combination of geometry and material was generated.

During the FEA1 analysis (figure 5), it was established that the highest stress calculated for the structure of the reference frame (175MPa) did not exceed the endurance limit of the material. This meant that the reference frame should have an infinite life under normal operating conditions. Since complex structures such as recreational product frames contain several types of joints (welded, riveted, bonded, bolted, etc.) the material properties, residual stress levels or the state of stress due to the stress concentrations are affected. These factors are not very often considered at the preliminary finite element analysis stage.

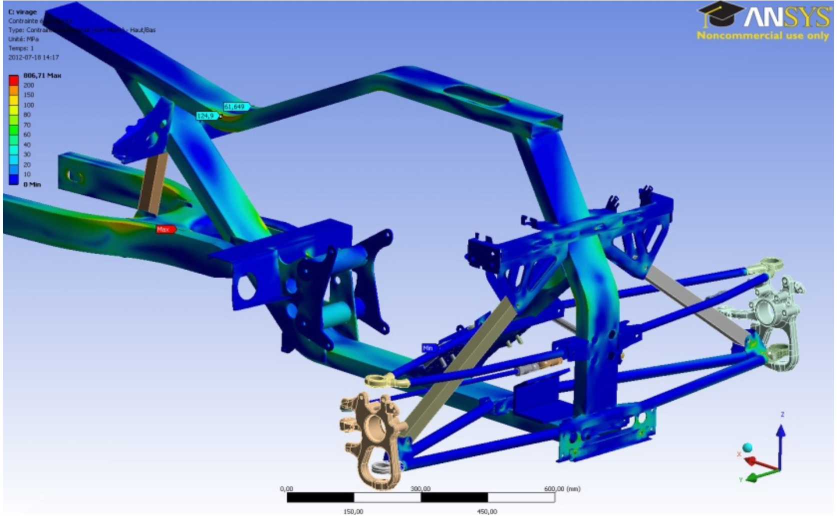

Fig.4: Finite element simulation of the frame with the actual loads (FEA1)

Due to the positive effect of the stress ratio, an optimistic assumption was made that the structure which was suspected to have an infinite fatigue life will really fall within this regime. Thus, a second finite elements analysis is required to establish the forces that would induce a fracture into the structure.

2.3.2. FINITE ELEMENTS ANALYSIS OF THE STRUCTURE WITH THE LABORATORY LOADING CONDITIONS (FEA_2)

With the finite element simulation of the product under laboratory tests conditions (FEA 2), the loads applied by the testing machine should produce the same stresses in the critical sections of the product as when using the service loads that were simulated in the previous step (FEA 1). To that end, a digital mockup of the mounting jig and frame was designed and modeled as shown in figure 5.

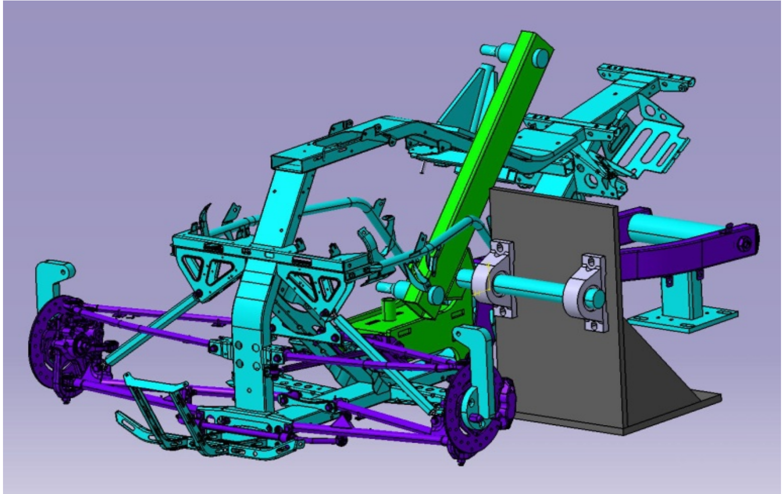

Fig. 5: The mounting jig and frame on the testing machine (DMU)

By calculating the loads to be applied on the testing machine, the engineers will also be able to identify the corresponding loads for a predicted service life in an accelerated test *(see the box «finite element model of the structure for laboratory tests»* FEA 2*).* Given the fact that the maximum stresses induced in the structure by the real service loads were under the endurance limit, it was decided to increase the forces in each load case to allow failures to appear.

As shown in figure 6, several points of interest were identified and compared to the results of the first simulation (FEA 1).

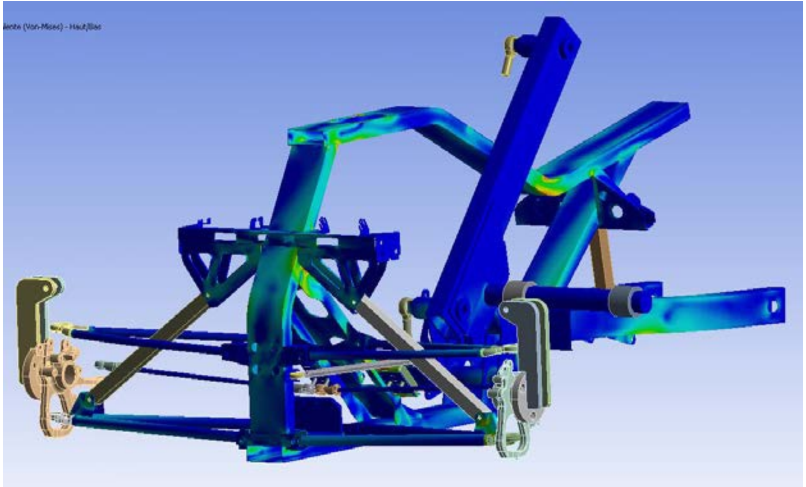

Fig.6: Finite element simulation of the frame on the testing machine (FEA2)

Therefore, simulation analysis FEA 2 allowed the engineering team to find the actuator forces that would induce a structural failure after the predicted lifetime of 425000 cycles. From this, a safety factor can be calculated from the ratio between the yield strength of the material and the stress induced by the actuator forces (determined for the desired lifetime).

The safety factor thus calculated can subsequently be used as criterion for the preliminary dimensioning of structural parts regarding service life. It should be kept in mind that this assembly *(chassis + jig)* must be designed in such a way that it should replicate as closely as possible the actual load cases. It can be seen in figure 6 (FEA2) that the loaded zones are indeed very similar to those from figure 4 (FEA1). In table 5, the results of this second simulation are presented for the critical points of the frame. However, it should be noted that, for confidentiality and liability issues, these points are not explicitly shown on figures 4 and 6.

Table 5: Results of the numerical simulation (FEA2) on the reference frame

Control points	**Braking + Bumps**	**Braking**	**Turning**
	σ (MPa)	**σ (MPa)**	**σ (MPa)**
P1	130	98	141
P2	86	80	126
P3	141	95	100
P4	135	118	169
P5	114	82	174
P6	192	185	195
P7	213	188	185
P8	201	198	242

Nonetheless, these steps of finite element simulations constitute the preliminary validation of the product *(virtual dimension)* and they will be followed by experimental and field tests *(physical dimension)*, to verify the correspondence between the numerical prediction of the product life and the results of the physical tests.

2.4. EXPERIMENTAL VALIDATION

The laboratory tests involve the application of the cyclic loads calculated at the FEA2 stage by the actual testing machine. These tests are used to validate the predicted life of the product and the estimated S/N curve of the chosen material. After performing several iterations at the numerical simulation step (FEA2), a physical prototype was installed and instrumented on the machine table, as shown in figure 8. The forces applied by the actuators depend on the type of test. The validation method allows us to perform extensive test *(based on the desired lifetime of the product)* as well as accelerated tests *(10000-50000 cycles)*.

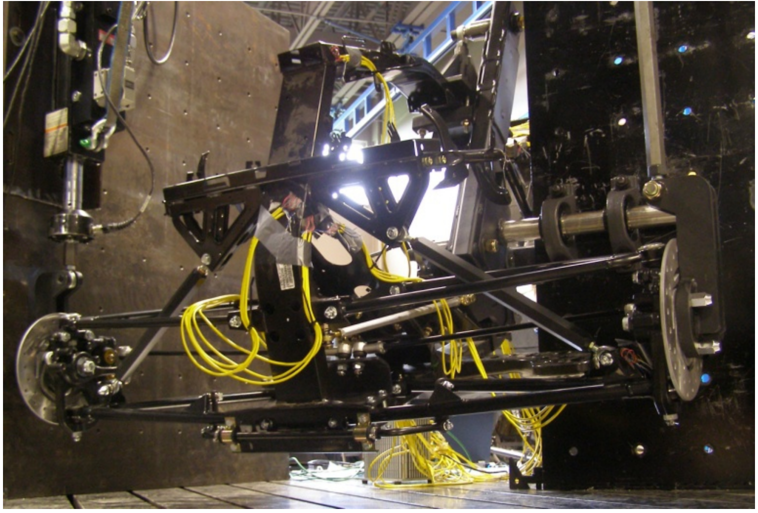

Fig. 7 The mounting jig and frame on the tests machine *(Physical prototype)*

The first step of this experimental stage was to identify the critical areas of the frame and the appropriate way to install the strain gauges *(orientation, position, surface cleaning, protection, etc.)*. Two softwares were used as tools to monitor the frame. These were TCE_v3.15 and EASE 3. A data acquisition system e-DAQ with 28 channels *(24 connected to the gauges and 4 connected to the control system of the testing machine)* was used to measure the equivalent stresses at the critical areas previously identified. The additional channels had been reserved to record the values of the applied forces and the actuators displacement. Indeed, the control system of the testing machine was connected to the e-DAQ system and the values of strains, stresses, displacements and forces were recorded synchronously and in the same data acquisition file. Figure 8 illustrates these data for the most severe load case applied to the frame assembly, featuring a combination of both flexion and torsion. The structure was attached to the testing machine table at 25^o in order to replicate the diving angle of the vehicle while braking. Before starting the test, it was necessary to ensure that the forces, applied by the actuators, were inducing into the structure the same stresses as those which were calculated at the FEA2 step. For this purpose, the calibration of all the gauges was necessary, followed by the verification of the stress values in the critical zones.

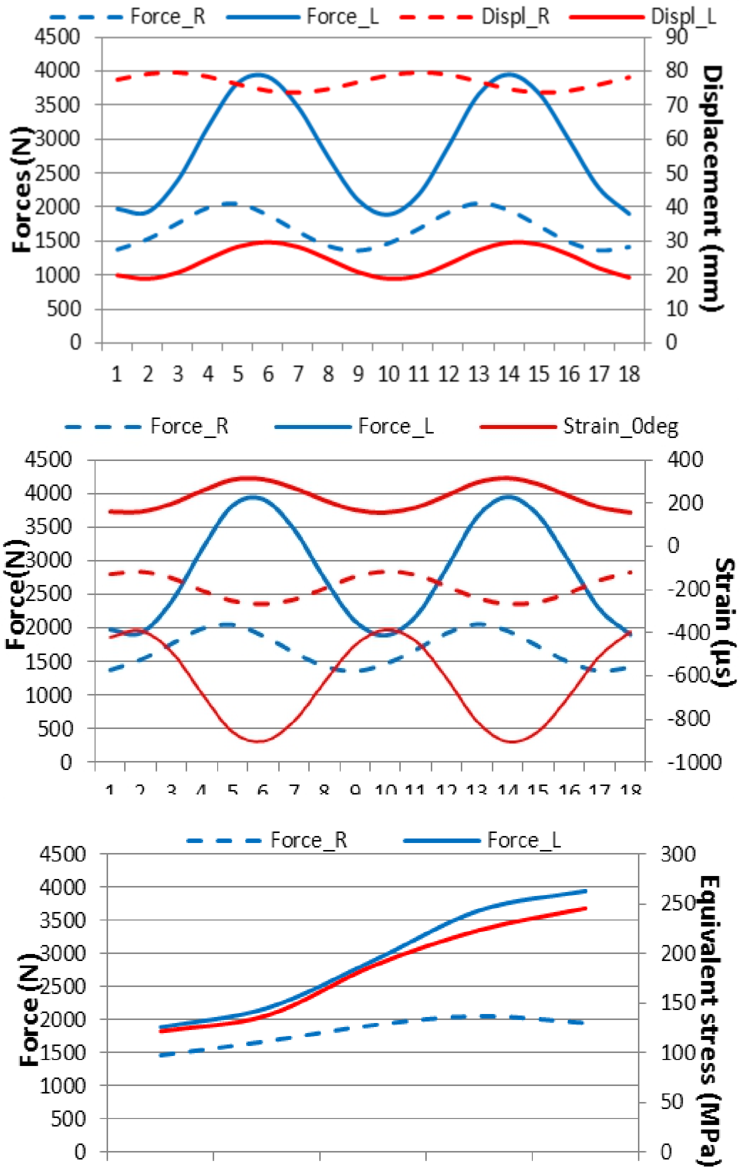

Fig. 8: Fatigue parameters from the acquisition data system e-DAQ

The calculation of the equivalent stress was performed using Hooke's, von Mises and Goodman's formulas as follows:

- To determine the internal deformation, the normal stresses and the shearing stresses, the Hooke's formulas were employed (1 to 6),

$$\varepsilon_{max.} = \frac{1}{2}\left[\varepsilon_a + \varepsilon_c + \sqrt{2\{(\varepsilon_a - \varepsilon_b)^2 + (\varepsilon_b - \varepsilon_c)^2\}}\right] \quad (1)$$

$$\varepsilon_{min.} = \frac{1}{2}\left[\varepsilon_a + \varepsilon_c - \sqrt{2\{(\varepsilon_a - \varepsilon_b)^2 + (\varepsilon_b - \varepsilon_c)^2\}}\right] \quad (2)$$

$$\varepsilon_t = \sqrt{2\{(\varepsilon_a - \varepsilon_b)^2 + (\varepsilon_b - \varepsilon_c)^2\}} \qquad (3)$$

$$\sigma_{max.} = \frac{E}{2(1-\vartheta^2)}\left[(1+\vartheta)(\varepsilon_b+\varepsilon_c)+(1-\vartheta)\sqrt{2\{(\varepsilon_a-\varepsilon_b)^2+(\varepsilon_b-\varepsilon_c)^2\}}\right] (4)$$

$$\sigma_{min.} = \frac{E}{2(1-\vartheta^2)}\left[(1+\vartheta)(\varepsilon_a+\varepsilon_c) - (1-\vartheta)\sqrt{2\{(\varepsilon_a-\varepsilon_b)^2+(\varepsilon_b-\varepsilon_c)^2\}}\right] (5)$$

$$\tau_{max.} = \frac{E}{2(1+\vartheta)}\sqrt{2\{(\varepsilon_a-\varepsilon_b)^2+(\varepsilon_b-\varepsilon_c)^2\}} \qquad (6)$$

- To determine the equivalent stress, von Mises formulas were employed (7 to 10),

$$\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{max.} - \sigma_{min.}}{2} \qquad (7)$$

$$\sigma_m = \frac{\sigma_{max.} + \sigma_{min.}}{2} \qquad (8)$$

$$\sigma_{eq\text{-}a} = \sqrt{\sigma_a^2 + 3\tau^2} \qquad (9)$$

$$\sigma_{eq\text{-}m} = \sqrt{\sigma_m^2 + 3\tau^2} \qquad (10)$$

- To determine the completely reversed equivalent stress, Goodman's formula were employed (11):

$$\sigma_{eq\text{-}CR} = \frac{\sigma_a}{1 - \frac{\sigma_m}{S_{ut}}} \qquad (11)$$

The calculation of the completely reversed, equivalent stress is necessary to predict the service life of the structure using the S/N curve. Since the S/N curves are determined through the application of an alternating and completely reversed stresses (tension/compression) applied to several specimens of standard sizes, Goodman's formula proved to be the best suited analytical tool for the calculation of the equivalent stress.

As predicted, the experimental test results have shown that the service life of the steel, reference frame is infinite and consequently, the structure is overdesigned. Indeed, after 425000 cycles the structure was still intact and functional. A structural failure eventually occurred after drastically increasing the applied forces above the upper limit of the initial load cases. Table 6 shows the results of each stress analysis step for the reference point P8 (the most critical) on the datum frame.

Thus, a comparison of these stress values allows an accurate evaluation of the structure while giving an idea of the robustness of the frame. In this case, the results of the experimental tests provide the confidence to further optimize the structure with respect to the weight reduction criteria.

Table 6: Stress calculations results for the critical point P8, at different stages of the PDP

	FEA_1	FEA_2	Experimental tests
Braking + Bumps			
P8	172 MPa	201MPa	232 MPa
Braking			
P8	168 MPa	198MPa	210 MPa
Turning			
P8	185 MPa	242 MPa	240 MPa

In the end, it should be remembered that the reference frame yielded after several spectrums of loads that far exceeded the actual forces acting on the structure under normal conditions of use. This confirms the findings presented in Table 3. In any case, a further reduction of the design safety factor could be considered, while still respecting the mechanical criteria.

2.5. PHYSICAL VALIDATION

Before the beginning of the production phase, physical tests are needed and some specific procedures are implemented. Physical tests are very expensive because they involve full scale infrastructures with professional test pilot riding on new vehicles assembled either in the prototype workshop or as small pilot run on the production line. However expensive this phase may be, it cannot be circumvented, as it provides a comprehensive feedback loop on the product and its specifications from a vehicle behavior and resistance point of view.

Finally, the ultimate validation of the product will be performed by the client himself *(client validation)* to ensure that its needs and the product specifications are fully satisfied. In this context, the client could provide his opinion of the product, relating to the design criteria of the manufacturer or designer, without being able to directly compare the new product with some competitor’s products *(in this case we are talking about an absolute validation approach).* On the other hand, the client could also express his opinion relative to competing products which are available on the market *(in this case we are talking about a relative validation approach).*

3. CONTRIBUTIONS OF THE APROACH TO THE PRODUCT DEVELOPPEMENT PROCESS

This paper is dedicated to the formalization and integration of design and validation activities at the detailed design phase of the design process. More specifically, the proposed methodologies focused on optimizing the service loads, the material and the geometry of the parts designed to be used on recreational products. Thus, in what follows, are outlined some contributions of the proposed methodology in both academic and industrial fields. Thus, in the academic field the new approach:

- Allows the design teams to reduce the time allocated to the detailed design process and to increase the accuracy of the product validation;
- Represents a very useful methodology and tool for training undergraduate students in mechanical engineering while improving the communication among the actors *(professors and students)* involved in undergraduate and postgraduate projects.

From another perspective, regarding the recreational product industry, four benefits from the proposed methodology have been identified:

- It provides a graphical planning tool *(Workflow)* for the various steps of the PDP, from the detailed design activities to the product final validation;
- It allows to allocate human, material and financial resources at different stages of the detailed design phase of the PDP;
- It makes it easier to communicate design and validation methods amongst various members of the organization *(managers, new engineers, technicians, etc.)*;
- Its iterative nature allows the correlation between the actual loads, the results of finite element simulations and the results of the experimental validation.

Moreover, the graphical representation of the different design stages will significantly facilitate the designers' tasks into the PDP, with the aim of reaching the ultimate objective of this process: product validation through numerical simulation and experimental testing. With the proposed approach, the product design and validation activities will also be conducted in accordance to the state of the art in the product development field (resources, methods and knowledge) to avoid both overdesign and poor design. The sources of information for the detailed design activities which have been formalized in this paper include design codes and formulas, handbooks, and components specifications from suppliers.

4. CONCLUSION

In the prescriptive design and validation methodology presented in this paper, iterations play a very important role in determining the material, shape and size of the new product or component. This imply the initial selection of a material, shape and size for a model, with the hope that the design criteria can be met and that strength, life and safety goals will all be achieved after successive controlled improvement to the initial proposition. Another important aspect to be taken into account by the designers is that of «design for X» where X is an attribute such as manufacturing, reliability, recycling, environment, etc. Since most products are designed to be built, sold, used and then disposed of, these attributes were collectively integrated in the proposed methodology as qualitative design criteria.

Moreover, the formalization of the PDP renders the design steps performed by the multidisciplinary teams much more explicit and better documented. Thus, the proposed methodology is very helpful for a good communication amongst all three parties in the **designer-manager-user** triangle, in which tasks such as analyzing, modeling, testing, evaluating, and optimizing are performed.

The most important goal that was reached with this approach is the correlation between the results of the load cases identification phase, numerical simulations phases (FEA1 & FEA2), and the experimental tests. This is also representing an original way to design, optimize and validate the product without overdesigning it and in the same time avoiding a poor design.

Future research activities will include:

- Integrating the proposed approach for other recreational products with the aim of improving the structural components of the vehicles;
- Developing more specific methodologies to eventually cover all areas of engineering *(propulsion, direction, braking, body or electrical system)*, and to support multidisciplinary teams as they improve and validate their designs.
- Integrating the proposed design and validation methodologies into the mechanical engineering curriculum at the Université de Sherbrooke (QC) with the aim to support and improve design education.

However, it has to be stressed that although the mentioned approach has not been formalized until now, it is already well understood and followed in industry while still representing an original contribution in the academic universe.

Finally, design and validation methodologies such as the one outlined in this paper, may also be a valuable tool in design learning and could show students the work of experimented engineers and help them reflect on their own design processes.

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