Metallic space-frame design and manufacturing for custom-made motorcycles: A test case

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Abstract : As with any high performance product, riders seek and deploy motorcycles with enhanced performance characteristics. This procedure is carried out mainly through customization of the comprising parts, especially when they are intended for race or leisure vehicles. Key element in this concept is weight minimization and stiffness maximization, while at the same time road performance and behavior are kept smooth and yet, at the same time, aggressive. The design process is iterative, and it concludes on both material and dimensions that can achieve these, incorporating road trial and test results. Modern CAD and FEM tools, when properly combined with experimental test results, can lead to a very small iteration cycle for final motorcycle part design and manufacturing. This study proposes a systematic methodology for fast development of new custom-design motorcycle frames. The methodology is then validated by building a frame from scratch, after proposing the appropriate software and hardware tools to achieve this**.**

***Keywords* - FEM, FEA, design, welding, manufacturing, space frame, customization.**

I. INTRODUCTION

The first motorcycle was manufactured in 1868 and its primary use was to transport people. Since the end of World War II, as the society and its needs were diversified, motorcycle races became official and widespread. Therefore continuous efforts have been put in to produce high performance motorcycles. Despite the relentless evolving technology and innovations, the manufacturers face a continuous need of improving the overall performance of the vehicle. Two top priorities were to minimize weight and to maximize the stiffness of the frame, with the perspective of increasing speed, acceleration, stability and safety. Significant researches have been conducted in weight reduction based on advances in materials, improved design and analysis methods, fabrication processes as well as optimization techniques. Design optimization has and should be utilized to accomplish a minimum weight with maximum performance founded on elimination of conflict constrains, design limitations, and design prerequisites.

A motorcycle frame is a motorcycle's core structure. The frame supports the major components and systems of the vehicle (front and rear suspension, swing arm, handlebar steering, engine, gearbox and all the secondary equipment such as battery, exhaust system, vehicle bodywork etc) and supports the rider. The racing motorcycle functions under extreme operating conditions, withstanding numerous forces and torques caused by bumping, braking and stressful acceleration. Therefore, in designing and optimizing a racing motorcycle frame we must i) minimize the weight, ii) maximize the strength, stiffness and durability, iii) centralize and lower the weight.

The design and the manufacturing process of a motorcycle frame are essential and pain-stacking, since the former greatly impacts its dynamic behavior. This process is performed in automated CAD and FEM systems, so that the final product obtains the optimal mechanical properties and a proper driving behavior. In previous studies, the static and dynamic properties of a motorcycle frame have been studied and developed thoroughly [1, 14, 22, 23]. There has been, as well, an extensive research to the steering and stability analysis of single-track vehicles [2, 3, 4, 5, 8]. For custom motorcycle frames manufacturing purposes, typical or empirical values are often taken into account [9, 10], thus resulting in achieving motorcycle characteristics that cannot determined beforehand. Numerous chassis construction research studies take loads, safety factors and other significant components [6, 7, 10, 21, 23] into consideration. Numerical methods [1, 12, 15] and particularly computational simulation work based on parametric finite element analysis methods [1, 13, 19, 23] have been applied to fatigue analysis, since it is proven as the appropriate approach on the field. Topology optimization has been, also, proven to be an effective technique in obtaining weight reduction of motorcycle frame [16].

The endeavor of achieving an innovating frame construction has been founded on the following objectives:

1. The custom motorcycle has been constructed adjusted the AMOTOE requirements [24], in order to be classified as a handmade racing motorcycle.
2. The construction of an innovative frame design
3. The minimization of weight [16].
4. The maximization of frame stiffness [6].
5. The optimization of driving behavior [8].

In this article, a production model [11] and a novel construction were combined based on the aforementioned studies. Thus, a complete method for creating custom motorcycle frames is presented, which is applicable not only to large production units, but also to small batches, even single part production, as it undertakes low production costs and implies production without advanced or specialized equipment. Applied materials are those as in high performance motorcycles. The design process aims at adequate frame stiffness for specific driving behavior models. The value of the proposed method is that it provides the necessary expertise and know-how in converting a factory-fitted motorcycle to one with improved features, as high performance motorcycles intended for racing, while retaining the desirable driving experience at the same time.

The frame geometry to be manufactured derives from the original motorcycle geometry and this needs to be improved; this means that parts such as wheelbase, height and rake angle are taken into consideration, as well as improved parts such suspension wheelbases are also considered. In that sense, a "new" model has been created by both complying with the original characteristics of the motorcycle and implementing improved - high performance components. The proposed frame design uses measurements from the motor and related published information. During the production stage, the engine is important because the frame is built on it without the need of a special jig.

II. GENERAL DESIGN FEATURES OF MOTORCYCLE FRAMES

The first step in this method is to obtain the engine measurements upon which the motorcycle is built, namely engine width, height and mounting points, either through actual measurements on the engine itself or through its documentation. These measurement help orient the engine volume on the motorcycle frame. The two-dimensional CAD drawing can be created on a proper parametric CAD software, such as SolidWorks®, based on documentation data, engine and improved components dimensions.

In this design stage, the basic design features are: (a) wheelbase, (b) rake angle, (c) ground clearance and (d) a point on the engine, designated as an Engine Reference Point (ERP). In the present study, a two-cylinder, four-stroke, eight-valve flat-bed motor is considered at 1,085 cc. The goal is the transformation of a touring motorcycle into a custom super bike for track use with a driving behavior similar to that of the original motorcycle. In a simplified drawing, Figure 1 depicts the ground clearance between road and engine -instead of the documented distance between road and ferring-, the wheelbase, the rake angle, the point A (center of the head tube) and point B (ERP). Frame boundaries derive from the 2D drawing (Fig.1) as the distance between points A and B on the X (longitudinal) and Z (vertical) axes.

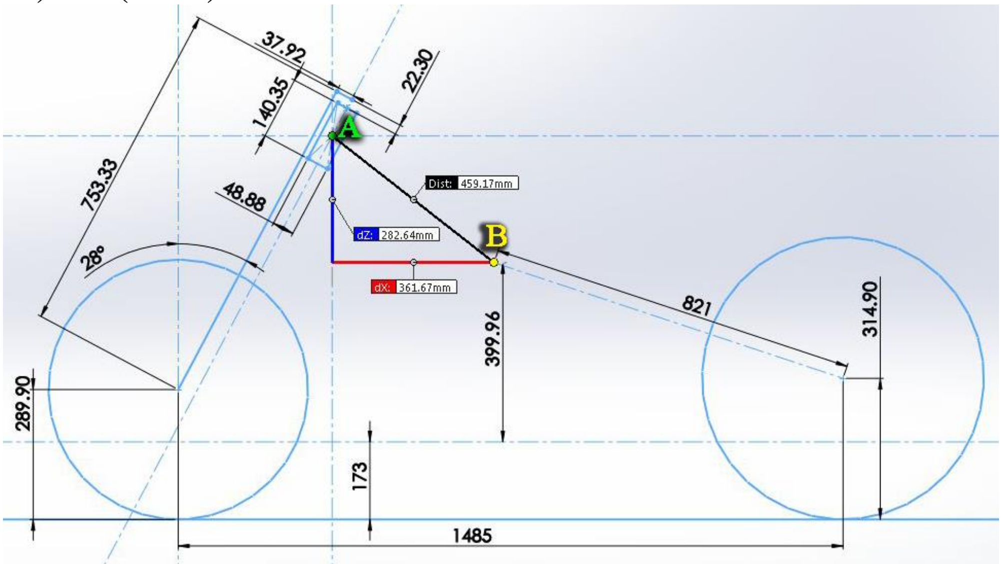

Figure 1. Basic motorcycle dimensions (in mm) in 2D.

Table 1. Motorcycle parts dimensions. *(*: refers to dimensions without any load).*

Description	Dimension (mm)
Front wheel tire*	299.90
Rear wheel tire*	324.90
Front fork*	783.33
Top fork bridge thickness	22.30
Top fork bridge offset	37.92

In the drawing (Fig. 1), neck center position (point A) is specified relative to point B. Relative coordinates in X and Z directions are X = 361.67 mm and Z = 282.64 mm. In accordance to the proposed frame design, spatial frame nodes (Fig.2) are obtained. Frame nodes are designed in a way that frame inclination represents the motorcycle inclination when standing. Frame design takes into consideration minimum construction complexity and minimum production costs. No more than three different metallic pipe profiles (cross-sections) are decided upon to be used for the frame, for production cost management reasons. Besides, all joining elements are straight.

III. FINITE ELEMENT MODELING AND ANALYSIS OF MOTORCYCLE FRAMES

The next step of the method is to define the applied loads on the motorcycle. Such loads are related to both suspended and non-suspended weights, including rider(s) weight. The weight of all components is needed and this can be obtained through manufacturers' catalogues. Also, it is important to properly define the positions where various loads are applied. Subsequently, a FEM static analysis of the frame must be carried out on an analysis software tool. In this case, SolidWorks was implemented to perform the analysis, but any similar software can be used instead. Finite Element Analysis (FEA) with application of appropriate loading scenarios leads to the proper selection of the frame's tubular sections. In this study, worst loading occurs during intense deceleration. The designed frame is not affected by acceleration, as it does not rely on the rear suspension, the rear wheel fork or some other component that is carrying the respective forces. Furthermore, due to engine axis of rotation (Z axis) and the way it is secured to the frame, the engine does not transfer moment of inertia to the frame. Consequently, static analysis results, taken for the most unfavorable loading, e.g. during braking, is enough to determine the frame behavior. Analysis criterion is to achieve a safety factor greater than or equal to 2. Weights and constants of the analysis are presented in Table 2.

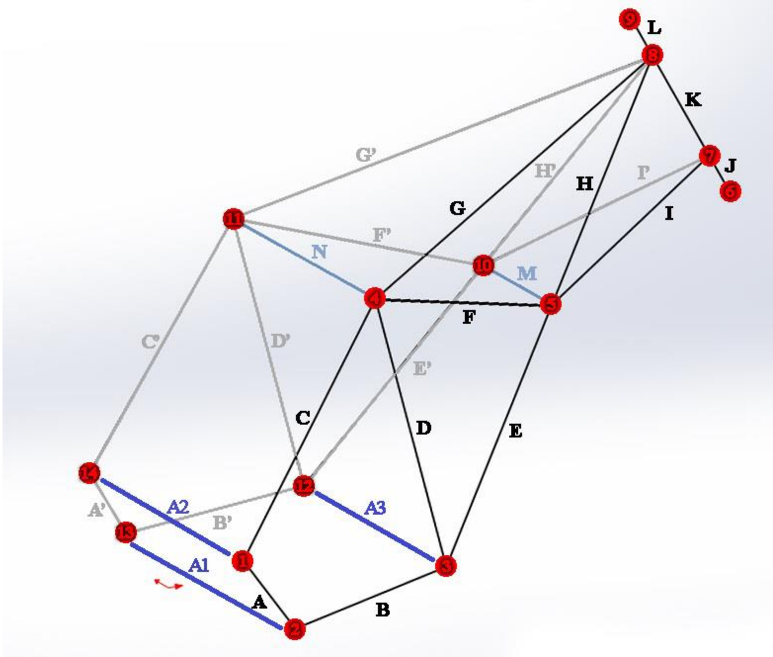

Figure 2. Nodes in the spatial frame.

Table 2. Various motorcycle parts weight and their application on frame nodes. Node numbers with respect to Fig. 2.

No.	Part	Weight (kg)	Node of application
1	Engine	63	1, 2, 3, 12, 13, 14
2	Gear box	12	1, 2, 3, 12, 13, 14
3	Front suspension	12	6, 9
4	Exhaust	5.6	1, 2, 3, 12, 13, 14
5	Oil tank	2	5, 10
6	Fuel tank	1	9
7	Fuel 20L	7.39	9
8	Engine oil 3.75L	3.5	1, 2, 3, 12, 13, 14
9	Gear box oil 1L	0.915	1, 2, 3, 12, 13, 14
10	Distance recorder	2.8	9
11	Handle bar	3	9
12	Electric system	14	1, 2, 3, 12, 13, 14
13	Injection system	4.2	1, 2, 3, 12, 13, 14
14	Head light	1.5	9
15	Stand	1.05	1, 2, 3, 12, 13, 14
16	Other	8.4	1, 2, 3, 12, 13, 14

3.1 Critical Load Analysis

When calculating static loads, it is assumed that the weight of the motorcycle-rider system is distributed equally between the wheels and that the center of gravity is above the middle of the wheelbase at a height measured from the road equal to half the wheelbase distance [13] (see Fig. 3). The equilibrium equations are stated as follows (Eq. 1 to 3).

$$F_f + F_r = m \cdot d \tag{1}$$

$$N_f + N_r = m \cdot g \tag{2}$$

$$N_r \cdot b - N_f \cdot (p - b) + F_r \cdot h + F_f \cdot h = 0 \tag{3}$$

Where:
F_f and F_r : Longitudinal forces on front and rear wheel respectively (N)
N_f and N_r : Vertical forces on front and rear wheel respectively (N)
p : wheelbase distance (mm)
b : center of gravity to rear wheel axis distance in longitudinal direction (mm)
h : road to center of gravity distance in vertical direction (mm)
m : total mass of motorcycle-rider system (kg)
g : gravitational acceleration (g = 9.81m/s^2)
d : deceleration (m/s^2)

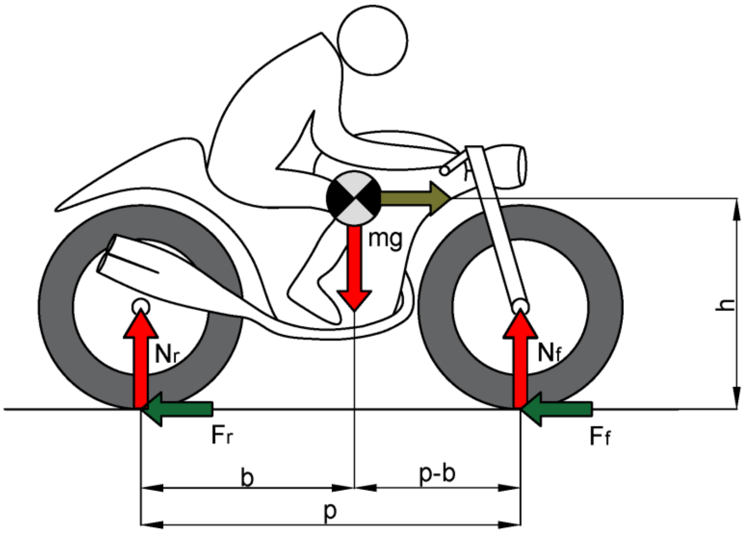

Figure 3. Applied forces during braking.

According to the assumptions in the last paragraph, we calculate $p = 2b$ and $h = b = \frac{p}{2}$. Before continuing with the calculations, the deceleration must first be found. As stated previously, the motorcycle is considered to decelerate, as this is the most unfavorable operation condition. Using basic motion equations, assuming that the motorcycle needs to come to a stop while traveling at 100 km/h in 3.25s, the deceleration is calculated d = 0.87 x g = 8.53 m/s^2.

The well-known friction equation, $T = F = \mu\, N$, applies to both front and rear wheel and, for the special case of deceleration, the friction coefficient is μ = 1.2 for both the front and rear wheel, according to diagrams found in [2].

Solving the system of Eq. 1 to 3 and replacing with the friction equation, we obtain the following formulas for N_f, N_r, F_f and F_r:

$$N_f = \frac{1}{2} m(g + d) \tag{4}$$

$$N_r = \frac{1}{2} m(g - d) \tag{5}$$

$$F_f = \frac{1}{2} m\mu_f(g + d) \tag{6}$$

$$F_r = \frac{1}{2} m\mu_r(g - d) \tag{7}$$

Replacing the known values and constants, assuming that the motorcycle weight is 200 kg and the rider's weight is 100 kg, thus the total mass m = 300 kg, then by solving Eq. 4 to 7, the values for N_f, N_r, F_f and F_r are obtained (see Table 3).

Table 3. Longitudinal and Vertical forces applied during motorcycle deceleration.

Force	Value (N)
N_f	2782.5
N_r	162.1
F_f	3339.0
F_r	194.5

3.2 Selection of frame cross-sections

First of all, material and beam cross-sections of the frame must be chosen. This process is iterative until the optimal solution for the beam cross sections is reached. Application of a static FEA is accomplished using the calculated loads in Section 3.1. A minimum safety factor needs to be achieved, based on the material properties. If the required safety factor cannot be achieved, frame design or beam elements cross section or even both must be modified. Then, after proper changes in the design, a new static FEA must be carried. This process is repeated until the required mechanical strength of the frame is achieved. For the present study, both versions of chromoly material 25CrMo4 and AISI-4130H have been considered in the analysis [12]. According to Fig.4, optimal cross section is found by examining the relation between weight per meter and material cost. Various circular cross-sections were tested sequentially through static FEA in SolidWorks® (Fig.4) until an adequate safety factor is obtained. These runs resulted in the use of a Ø30x2.0mm (outside diameter x wall thickness) tube for the frame construction and, at the same time, a Ø48x5.0mm tube for the neck construction. The cross-section Ø48x5.0mm does not correspond to a standard pipe dimension, so it is to be manufactured on a lathe.

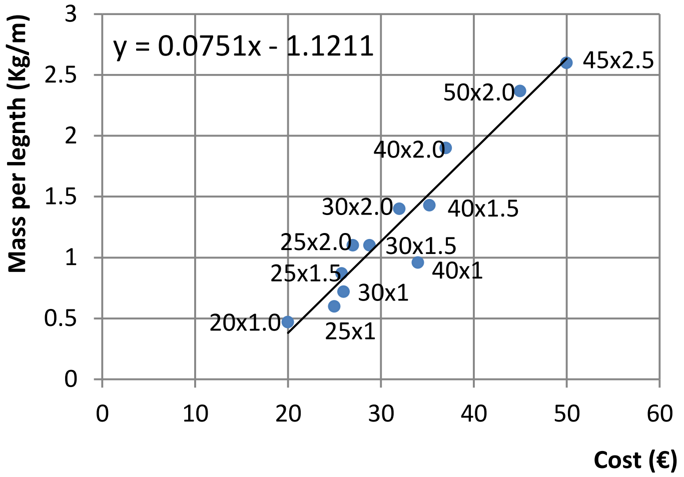

Figure 4. Material cost to mass per length relationship for various cross sections and trendline equation.

Table 4. Static FEA results.

No	Description	Value
1	Minimum factor of safety	2.1
2	Maximum stress	217.2 MN/m^2
3	Maximum deformation	0.265 mm

Table 5. Designed dimensions of beam elements used in the analysis and respective node connections.

Element	Length (mm)	Connected Nodes
A (A')	60.748	1, 2
B (B')	127.656	2, 3
C (C')	199.124	1, 4
D (D')	202.853	3, 4
E (E')	198.498	3, 5
F (F')	174.961	4, 5
G (G')	306.110	4, 8
H (H')	188.786	5, 8
I (I')	171.182	5, 7
J	26.695	6, 7
K	86.960	7, 8
L	26.695	8, 9
M	108.411	5, 10
N	222.400	4, 11
H'	188.786	8, 10

Fig. 5 depicts the final model stress analysis results, the safety factor distribution (based on Von Mises stress criterion), as well as, the deformation distribution. The smallest safety factor is slightly above two (2), according to the design requirements. As expected, the high stress concentration (critical) area of the structure is the attachment of the frame to the neck-tube.

IV. Tooling and Frame Construction

During the present study, an integrated design-analysis-manufacturing method for the production of custom frames is developed, taking into consideration cost-related issues. In such custom or single part productions, mainly conventional tools and machines are utilized, since acquisition costs for general use automated tools are very high and disproportional to the possible market value of a single part, unless a very large number of custom parts are to be produced. The proposed method does neither include dedicated equipment nor specialized personnel to handle it, thus construction costs are kept to a minimum. However, the utilized methods and tools are appropriate to successfully achieve required frame production quality.

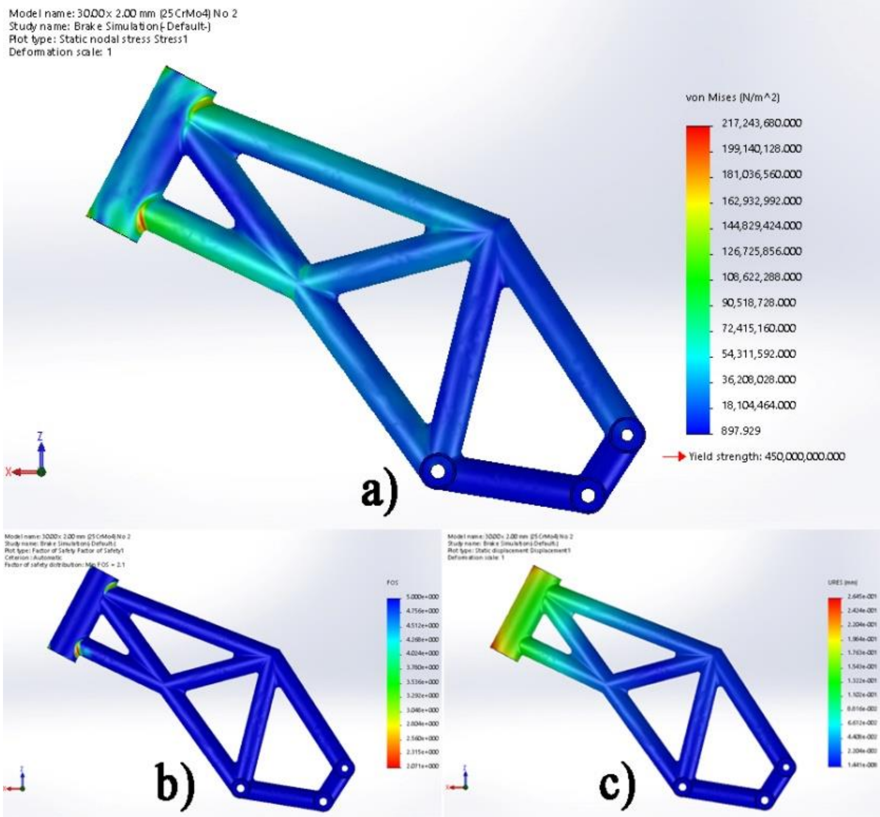

Figure 5. Frame FEA results. a) Stress, b) Safety Factor, c) Deformation.

The required tools and materials are the listed, as follows:

A. **Angle grinder** for cutting and shaping frame elements. An adequate power value is $800W$. A $4\ ^{1}/_{2}$" angle grinder is preferable, that weighs less than $2\ kg$. Speed adjustment is not necessary, but makes the shaping procedure easier. A cutting disk $120 \times 1\ mm$ with $80\ m/s$ is recommended. For tube forming, a grinding wheel $120 \times 5\ mm$ at $80\ m/s$ is recommend.

B. **MIG-MAG Welder** for welding frame elements. Output current should not exceed $120A$. Synergic type devices with $5\ kg$ wire capacity are preferred. Welding material may be the same as the base metal or, alternatively, one with a higher yield stress.

C. **TIG Welder (optionally).** It can be used as a technique for weld finishing without grinding. Output current does not need to exceed $120A$. This welding method is used for local improvement of welds, which are created by MIG-MAG. Otherwise, local grinding should take place to improve the weld, then reuse the MIG-MAG.

D. **Lathe (optionally)** for constructing neck and special elements on the support points, such that of the engine. An adequate power value is $550\ W$. Suitable tool is the one with a spindle bore of $20\ mm$ and distance between centers $550\ mm$. Otherwise, required parts can be outsourced to a machine shop at a relatively low cost.

E. **IPN beams** for securing the engine to the ground during frame construction. Two $2\ m$ long size No 80 are used. The two steel beams are placed parallel to each other and parallel to the ground. Then, the engine is placed on the beams with a proper inclination.

F. **Bolt and nuts** for head tube fastening. Its diameter should be less than the inside diameter of the head tube. The bolt is positioned at the dead center of the beams, in front of the engine and at an appropriate distance, inclined at the same angle as the rake angle.

G. **Cutting Stencils.** Using CAD software, a proper conical section is printed for each element and it is used as a tube cutout pattern. Then, using the angle grinder with a cutoff wheel, the conical sections are cut on the tube to form the frame elements. Instead of creating stencils, online calculators can be used.

With the tools listed above, along with wrenches, screw drivers and hammers, it is feasible to build the frame, so as to use it as proof-of-concept for the method. The frame can thus be built upon the engine and IPN beams, without using a universal jig. The engine is used as a fixed and fixing part and all frame components are supported by it, except for the head tube. The assembly process includes the following steps:

1. The IPN beams are securely fixed on the ground parallel to each other.
2. The engine and the head tube are placed at appropriate distances (see Fig. 6).
3. The node joining tube elements are cut at proper dimensions and their ends formed with the angle grinder using the stencils.
4. Head tube is created on a lathe.
5. Each tube element is positioned on the jig and spot welded with MIG-MAG at 8 points, so that it stays in place. Special care must be taken so that they do not move owing to thermal expansions during welding and contractions during cooling.
6. After all elements are placed and spot welded, full welding is carried out with a MIG-MAG welder.
7. Finish welding all elements with TIG. This method does not remove any material from the weldings, thus maintaining the safety factor.
8. Inspection of the construction (see Fig. 7)

Figure 6. Using engine and steel beams as a jig for frame construction.

Figure 7. The welded frame.

V. RESULTS AND DISCUSSION

An econometric analysis and error estimation is performed to assess the method efficiency. Constructed frame parts are measured and compared to the theoretical ones, as derived from the drawings. In addition to frame materials, cost of implemented “auxiliary” materials for jig construction, such as beams, bolts, etc. has also been estimated. Table 6 lists all materials that contribute to the frame construction, except for consumables.

Table 7 depicts the analysis of frame production costs. Cutting tools, regardless of the fact that they can be used for a number of parts, are included to cover for machine usage and maintenance costs. For the same reason, welding material cost is considered 10% higher than actually used. Moreover, Table 7 provides the detailed cost of consumables, materials and labor including loss. In this analysis, costs involving tool and machine acquisition are not included, as it is not reasonable to evaluate equipment depreciation based on single part production.

Table 6. Required materials, quantities and costs

Description	Quantity	Price / Unit (€)	Cost (€)
IPN Beam No 80	1	30/6m	30.00
Screw 30x4 mm	1	17.36/m	17.36
Screw 16x1.5 mm	1	2.80/m	2.80
Screw 12x1.25 mm	2	1.60/m	3.20
Screw 10x1.25 mm	2	1.30/m	2.60
Nut 30x4 mm	4	3.38	13.52
Nut 16x1.5 mm	6	1.40	8.40
Nut 12x1.25 mm	10	0.22	2.20
Nut 10x1.25 mm	8	0.18	1.44
Material 1.7218	6	32.26/m	193.58
Material 1.0301	0.2	10/m	2
Total cost			**277.10**

Table 7. Frame Production Cost analysis.

Description	Quantity	Unit	Price / Unit (€)	Cost (€)
Geometry calc.	0.5	h	10	5.00
Load calc.	0.5	h	10	5.00
3D design	3.5	h	10	35.00
FEA	0.45	h	10	4.50
Material 1.7218	4.2	m	19.77	83.05
Material 1.0301	0.2	m	7.6	1.52
Material 1.7130	0.3	m	6.08	1.82
Frame Constr.	6	h	10	60.00
Head tube Constr.	0.25	h	10	2.50
Element Constr.	5	h	10	50.00
Cutting disk	3	piece	0.60	1.82
Grinding wheel	2	piece	2.05	4.10
Drill bit	4	piece	2.28	9.12
Wire MIG 1.512	0.82	m	1.56	1.28
Anti splatter spray	1	lt	3.42	3.42
Nozzle 1mm	2	piece	2.5	5.00
Inert gas	2700	lt	0.0038	10.26
Welding	8	h	10	80.00
Painting	1	h	90	90.00
Sand paper	3	piece	0.34	1.02
Thinner	3	lt	2.28	6.84
Wash primer	0.25	lt	13.68	3.42
Surfacer	0.5	lt	13.68	6.84
Paint	0.25	lt	38	9.50
Hardener	0.25	lt	20.52	5.13
			Total cost	**486.14**

Table 8. Element measurements and respective error estimation. Values with (*) cannot be measured.

Element	Study (mm)	Real (mm)	Deviation (mm)	Deviation %
A (A')	60.74	60.74	0.00	0.00*
B (B')	127.65	127.65	0.00	0.00*
C (C')	199.12	200.00	0.88	0.44
D (D')	202.85	205.00	2.15	1.05
E (E')	198.49	200.00	1.51	0.76
F (F')	174.96	178.00	3.04	1.73
G (G')	306.11	305.00	1.11	0.36
H (H')	188.78	200.00	11.22	5.94
I (I')	171.18	170.00	1.18	0.68
J	26.69	26.58	0.11	0.41
K	86.96	86.85	0.11	0.12
L	26.69	26.58	0.11	0.41
M	108.41	127.00	18.59	17.14
N	222.40	225.00	2.60	1.16
A1	220.00	220.00	0.00	0.00*
A2	197.00	197.00	0.00	0.00*
A3	179.00	179.00	0.00	0.00*
Rake angle	28.00°	25.80°	2.20°	7.85
Head tube	90°	90.23°	0.23°	0.25
			Average deviation	**1.76 %**

The two most significant errors in the constructed frame appear in the rake angle and the normality of the neck. The rest are considered negligible, since they do not affect the driving behavior of the motorcycle. In specific, error of almost 2.20° at the steering angle, results in a 34 mm reduction in the wheelbase and a 16.87 mm increase in the height of the motorcycle. Deviation from the normal for the head tube by 0.23° results in an offset between the front and rear wheel of 2.00 mm. The average deviation of 1.76% is well within quality limits, as it in fact does not affect the overall production quality or the behavior of the motorcycle, as road trials proved.

VI. Conclusion

In this study, a systematic procedure for the design and manufacturing of prototype motorcycle frames is proposed, that could be easily followed by either professionals or amateurs efficiently. The method includes designing, analysis and manufacturing of any motorcycle frame of the same type. In order to perform the analysis stage, the established philosophy of CAD/CAE technology needs to be implemented. In this case, SolidWorks® software was used, since it is a proven and reliable professional tool that has more than enough been used for obtaining stress and deformation values on parts and assemblies. The mathematical section for load calculations utilizes basic mechanical equilibrium equations, so as to be easily handled and to deliver safe and undisputable results. During the actual frame construction, tools, machines and methods were typical ones and of reduced cost. Applying this overall method leads to the conclusion that using a simple jig that comprises of a motorcycle engine and steel beams reduces: (a) frame manufacturing costs, (b) manufacturing and assembly time, and at the same time, c) risk of error during the processes.

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