STRENGTH CALCULATION OF FIXED JOINTS APPLIED IN PASSENGER CARS

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Abstract: The paper describes mechanical joining methods used in car body production. The automotive industry is a decisive industry and a driving force for the development of the Slovak economy. Mechanical connecting is the most widely used method of connecting materials. Joints are a critical factor in the production, assembly and service of cars. The joining in car body is mainly used to join material with various thicknesses, mechanical properties, surface coatings, even ferrous or non-ferrous metals. Many requirements are placed on the body of the car, the important thing is sufficient stiffness of the structure under the given stress. The paper deals mainly with welded and glued joints in the design of automotive structures and their strength analysis using the finite element method.

Keywords: welded joints, glued joints, car body, FEM.

1 Introduction

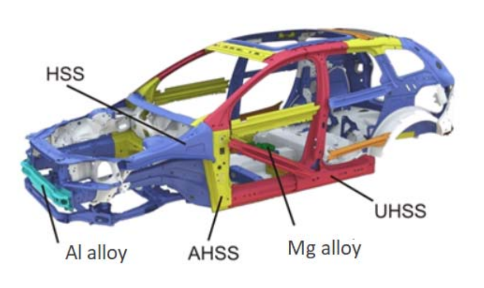
The automotive industry is a decisive industry and a driving force for the development of the Slovak economy. The effort of designers in the automotive industry is to use a material that would meet the lowest possible weight without compromising the safety of the crew, ideally with the lowest possible production costs. The purpose of all regulations is to ensure the greatest possible operational safety of the vehicle, therefore the car body is a complex product [1, 2]. Many requirements are placed on the car body, such as sufficient rigidity of the structure (stress, safety and durability), minimal weight (material saving), protection of crew and cargo from weather conditions (closed car body), small vibrations, good view for driver, minimizing noise emissions inside the car body, easy and fast assembly and disassembly of damaged car body elements [3].

Reducing car body weight is one of the main goals in car body design. We do not encounter such a variety of materials used for car body construction anywhere else in any mass-produced engineering product. The construction of a car is made up mostly by steel of various qualities and properties. Steel makes up more than 80% of a car's construction [4]. Table 1 shows selected steels that are used in the automotive industry, although it should be noted that there is no categorization of unconventional automotive steels yet. Thanks to its properties, steel is a suitable material for car bodies construction, and thanks to its low price (compared to other suitable materials), it is also the most used material. Recently, extremely strong steel is also used - this type of steel differs from the others in that it is not made to achieve a specific chemical composition, but to achieve certain properties [5 – 8]. This type of steel also became the basis of ULSAB (Ultralight Steel Auto Body), which is basically a program aimed at demonstrating the properties of this type of steel, and the results are quite positive - 19% weight reduction, increased strength all together at a reasonable cost.

In 1970, plastics accounted for 6% of the car's weight, nowadays this share has increased to 25%. As the number of vehicles produced grew, so did the total consumption of materials. The average weight of road motor vehicles has been declining since the 1970s. The average European vehicle weighs almost 1,100 kg, with ferrous metals (60%), non-ferrous metals in particular aluminum (7%), plastics (10%), rubber (4.5%), glass (3%), textiles and anti-noise mass (4%), paint and putty (1.5%), liquids and other materials (7%). The material currently represents 30% of the production cost, so there is a great effort by manufacturers to reduce its consumption [9]. A favorable argument for the use of plastics in car production is the recyclability of all thermoplastics. At present, up to 90% of extracted oil is used for fuel production and only 10% of oil is processed in plastics production. Plastics are an environmentally friendly solution for car production and make a significant contribution to reduction of CO2 emissions.

Table 1. Selected steels used in the automotive industry

Strength class	Yield strength Re [Mpa]	Fortress limit Rm [Mpa]
Steel with low strength	< 210	< 340
High-speed steel (HSS)	210 - 550	270 - 700
Advanced High-Strength Steels (AHSS)	> 550	590 - 980
Ultrahigh-Strength Steels (UHSS)	> 550	> 980



The development of nanotechnologies and the decline in the price of nanocomposite materials with new possibilities for industrial production have influenced the construction of cars [10]. Due to the rapid development of nanocomposite polymeric materials, new materials with "tailor-made" higher mechanical and surface properties, and non-flammability have been created, the application of which has revolutionized automobile production. At the same time, new technological procedures were created in the production of car bodies, which made it possible to produce precise and also very complexly shaped parts from plastics with high resistance to the effects of mechanical stress in the event of an impact, resp. with very high impact strength. Plastics in conjunction with nanotechnologies in automotive manufacturing expand the range of properties of used plastics and textiles. Nanotechnological processes of the used plastics are often associated with high hydrophobic properties of exotic plants, which are referred to as the lotus effect [11, 12]. In automotive construction, physical properties of used nanocomposite polymeric materials are improved mechanical strength, improved abrasion and scratch resistance, reduced friction, dirt repellency, and anti-reflective character. These properties offer a wide range of possibilities for introducing innovations in car construction, including the use of nanoparticle-reinforced plastics, scratch-resistant paints, non-fogging surfaces, e.g., glass and anti-reflective surfaces, e.g., dashboard cover.

The use of plastics is also associated with innovations that are intended to increase safety, comfort and increase environmental friendliness. At present and also in the near future, the use of special composite reinforcement materials in car bumpers is expected, which show three times higher rigidity and energy absorption than ordinary plastic. Plastic headrests contribute to greater passenger safety [13]. In the event of a kickback, the front half of the headrest moves forward as a result of activation, reducing the risk of personal injury in the car. The main use of new materials or existing materials by replacing e.g., metals require a number of tests and experiments of their effective and efficient use. New trends in car development are focused on the use of new, lightweight or composite materials, for special surface treatments of car bodies, the use of light metal structures as well as for increasing the share of plastics for the assembly of modern types of cars. From the production-technical point of view, plastic composites filled with natural fibers of flax, cotton or sisal proved to be the best. By using these composites, great profile stability of the manufactured parts, their good impact safety, minimal emissions in the interior and high dimensional freedom are achieved.

In recent decades, great efforts have been devoted to the research and development of unconventional materials, mainly of composite materials [14, 15]. Due to the large prevalence of composite materials, there is also a growing need to combine them with other materials, such as metals. The reason for connecting may be increasingly demanding requirements for the mechanical properties of structures, which would not meet these materials separately.

Time plays an important role in car construction. Therefore, the aim is to use the most effective - the fastest ways of joining materials in the production of automotive parts, or in the construction of the entire car body. However, the speed of joining materials and welding must not increase at the expense of the quality of joints and welds [16 - 18]. Automotive production is one of the driving forces of the growth of the world economy. The production of some of the crucial parts of cars - axles and other chassis parts, but especially complete car bodies is based on the wide use of welding and joining technologies. The car body is considered to be a thin-walled construction, which should guarantee car users a high degree of safety while applying the trends of material and energy savings. The production of cars with lower weight and thus with lower fuel consumption, follows the ecological requirements of reducing materials of various thicknesses and qualities (projects of ultralight steel car body - ULSAB), whether plated or unplated, but also the connecting of ferrous and non-ferrous metals. Their application in the automotive industry opens new opportunities for designers. These consist in the optimal use of the properties of different types of sheets, which can be combined into one unit and thus affect the strength, stiffness or resistance to corrosion and resistance to chemical aging in different parts of the mold.

2 Application of joining materials in the automotive industry

In the automotive industry, it is necessary to combine materials of various qualities and thicknesses, whether plated or unplated, but also ferrous and non-ferrous metals. Thus, in addition to traditional steel, wider use is given to aluminum, carbon, magnesium, high-strength steel and also plastics. With conventional methods of connecting materials, such as spot resistance welding or laser welding, it is not always possible to ensure the required quality of joints. That is why companies are exploring alternative methods of joining materials.

Conventional methods of joining materials in the automotive industry include welding, laser welding, soldering, and gluing.

In practice, unconventional methods of joining materials in the automotive industry are used. Such mechanical, unconventional methods include, for example, the Clinching, ClinchRivet (CR) circular press, and the Self-Piercing Riverting (SPR) circular press.

Joints are a critical factor in the production, assembly and service of cars. Each joint causes disruption of the geometric structure of the material, both in composite and other types of materials. These discontinuities cause load transfer problems and increase in stresses at critical points in the material. This, in addition to reducing the service life of the material, also causes an increase in noise and vibration.

Mechanical connecting is the most widely used method of connecting materials. However, it has many disadvantages. These disadvantages are, for example, the increase in the weight of the structures due to the need to enlarge the joints, the stress concentration at the joints, the risk of galvanic corrosion (especially in the case of CFRP), the possibility of delamination in the production of holes, differences in thermal expansion of different types of joined materials. The main advantages of this type of material connections include the possibility of disassembly of the connected parts.

The adhesive method of joining materials (gluing) has experienced great development in recent years. This is mainly due to the availability of new high-performance mixtures based on polymers, which properties can be changed according to the specific requirements for individual types of connected materials. By bonding with adhesive mixtures, a longer service life of the connected parts can be achieved compared to parts connected by mechanical connections, which is related to the transfer of load from material to material along the entire length of the connection without discontinuity in these materials. This type of connection provides good sealing properties. Thanks to the flexibility of the adhesive mixtures, it is possible to reduce vibration and noise and also to optimize the strength characteristics of the connected structures. Disadvantages of adhesive connecting include the inability to disassemble connected parts and the need to prepare the surfaces of connected materials.

Welding technology is mainly associated with metallic materials. However, there are also polymeric composite materials (thermoplastic matrix composites) that can be connected by this technology. The advantages of welding are good mechanical properties and resistance of joints, short processing time and minimal need to prepare connected surfaces. The main disadvantages of this type of connection for composite materials are the restriction exclusively to thermoplastic materials, problems with the disassembly of connected parts and the presence of foreign substances in the structures of materials needed for individual types of welding (induction, resistance, ultrasonic). Laser welding is also increasingly used in the automotive industry (Fig. 1).

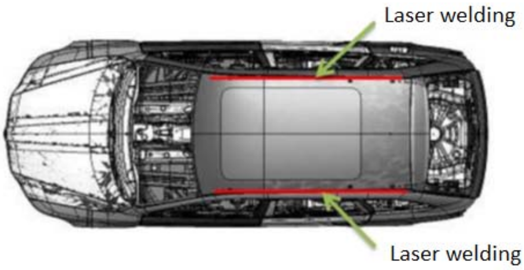


Figure 1. Laser welding on the roof of the car

Glued joints appear in the automotive industry in many types, both in terms of functional stress and in terms of design. It can be said that the bonding either acts as a complementary and sealing function (bonding and cementing of bodies for sealing, vibration damping, corrosion protection, application of reinforcements) or, in specific cases, can generally represent welding technology in structural strength joints [5]. Some applications of glued joints can be seen in Figure 2.

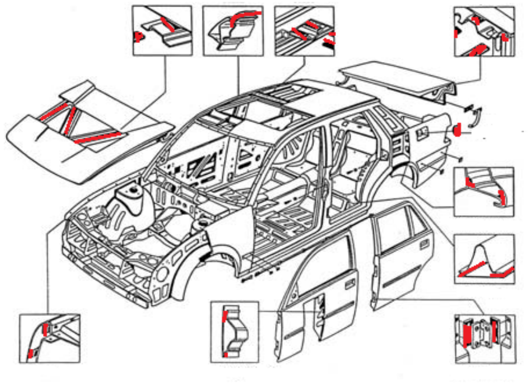


Figure 2. Glued joints of the car body

By using the bonding technology we avoid these problems and we can take advantage of the many advantages it offers in the automotive industry. Such as the possibility of new assembly procedures, reduction of the resulting weight of the car, preservation of the protective layer of zinc, higher strength and rigidity of the body, high quality of appearance of the parts to be joined and substantial reduction of noise in the car body.

It also has number of complications with the use of bonding technology in car body construction. For example, the adhesive must be overpainted, due to production, short time intervals to cure the joint, the adhesive life must be longer than that of a car, the adhesive must have sufficient strength, the shrinkage of the adhesive during curing on the car body surface.

The nature and composition of the adhesives used to build the car body is always firmly linked to the desired function of the joint. In this way, the adhesives can be divided into strength, reinforcement and sealing. Strength adhesives cure together with body paint. The edge adhesives are partially cured by induction heating during assembly, but full hardness is achieved only during the curing of the varnish by high temperatures in the furnace. The designer currently has a choice of many types of adhesives with different mechanical properties, ranging from tensile to brittle behavior. In the automotive industry, we are particularly interested in strength adhesives.

3 Use of FEM analysis for weld joints

The finite element method (FEM) is a method, which is widely used in engineering and mathematical modeling. Principle of This method is numerical solving of differential equations. The most used utilization areas for this method the traditional fields of structural analysis, heat analyses, fluid flow, mass transport, and electromagnetic potential. The FEM is generally a numerical method, which solves partial differential equations in two or three space variables. FEM solving process consists of subdivision of large system into many smaller and simpler parts, which are called finite elements. Software reaches this subdivision by discretization of a particular space in a given area or space dimensions. Result of such discretization is creation of a mesh on such object. Created mesh has finite number of elements of equal size, hence the name finite element method. FEM then defines a boundary value problem in a algebraic equations system. The method approximates the unknown function over the domain. [19]

In this work, a finite element approach based on Solid Works software is used to simulate strength of laser welded joint. Simulations are carried out for every combination of four materials.

3.1 Creation of the weld joint model

Geometrical model was made to be identical to pull test. The first step was to make a 3D volume object of o sheet metal plate with dimensions 100x25x0.8 mm (Fig.3).

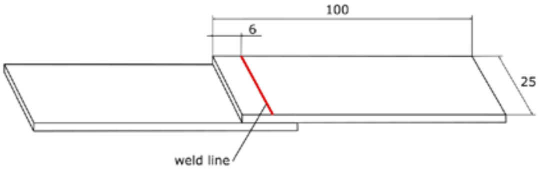


Figure 3. Sketch of welded plates with dimensions

Then, split lines were created to represent weld line and divide line, which define area attached to the test machine and machine arm. Attached area is 30mm of sheet metal length and full sheet metal width (Fig.4). This model was then transformed to sheet metal part, which represents it by a midplane in a FEM analysis. Fem analysis was carried out in assembly, where 2 sheet metal were aligned properly and mated.

Figure 4. 3D model of sheet metal plate

Simulation type was chosen to be static. Both sheet metal plates were checked their definition by shell manager. After making sure plates are defined as mid planes, connections were set. In connection settings, the global contact was set to no penetration and lap weld was defined by the edge weld situated on a weld line (Fig.5).

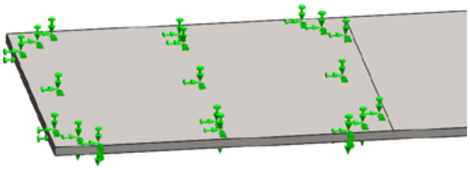


Figure 5. Fixed side of sheet metal plate

For fixtures, the command fixed geometry was set on the faces created on one metal plate, simulating attachment to the test machine. Fixed geometry fixes movement in any direction and rotation around any axis (Fig.6).

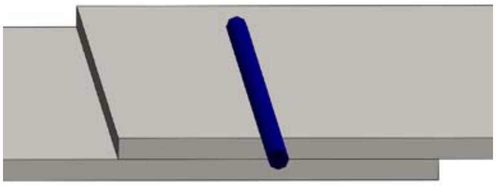


Figure 6. Weld spot and representation

For external loads simple command force was defined just like fixture, but on the second metal plate (Fig.7). Force was placed on both sides of metal plate and amount of force was set to total which distributes force on both sides equally. One of the last settings for simulation was to set materials to each sheet metal plates, which will change later in the simulation according to simulated pair of sheet metal plates.

Figure 7. Pulled side with applied force

Meshing has a big impact on results of the FEM analysis. Sheet metal plates will be represented as mid planes, which means mesh will be drawn as 2D. Solid Works is capable to draw only tree point entities and given the intricate dimensions of sheet metal plates, the meshing was difficult to define. To erase or minimalize any local maximums (stress). With this in mind the mesh parameters were set to 5.408 mm for global size and 0.27 mm for tolerance (Fig.8). This setting made negligible difference to local maximum in node to other values in close proximity nodes.

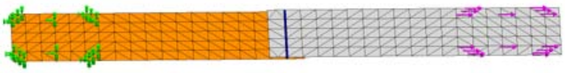


Figure 8. Sheet metal pair with mesh

Applied force for sheet metal pair was constantly changing according to examined pair materials. At the start the theorical numerical values for lap weld were computed for each material, which are F_e force for yield strength of the weld joint and Fm for ultimate strength of the weld joint (Table.2). Force Fe represents the maximum theoretical force, which can be applied to reach the yield strength. Fm is analogical to Fe but for ultimate strength. These values were then applied in FEM analysis for each material used in pair of sheet metal plates.

Table 2. Computed forces with material properties

Material	Re	Fe (N)	Rm	Fm (N)
HX340LAD	414	8280	473	9460
TL1550-220	292	5840	373	7460
HCT600X	346	6920	654	13080
DC04	197	3940	327	6540

After application of Fe and Fm the last thing to get from the Fem analysis was the force, which would be destructive for the weld and it would snap. Thou Solid Works do not dispone of such function to make a plot for maximum force until the weaker material breaks, the workaround had to be made. This workaround was composed of two parts. First part was driven by new result plot, which was factor of safety plot (Fig.9). If this factor of safety is set to be 1 for the weakest material in a pair. This means that the applied force is exactly at yield strength. If the factor of safety is anything else than number one, the force must be multiplied by the lowest factor of safety value. Second step was to determine coefficient between ultimate strength and yield strength by division. Multiplication of this coefficient and force for factor of safety equal to one gives the force load under which the weld joint breaks.

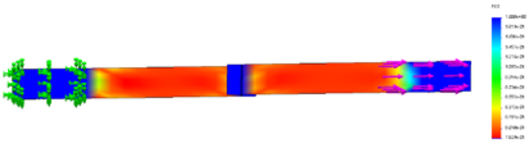


Figure 9. Factor of safety for TL-TL pair

3.2 Results of FEM analysis

Results gained by the FEM analysis are shown In Table 3.

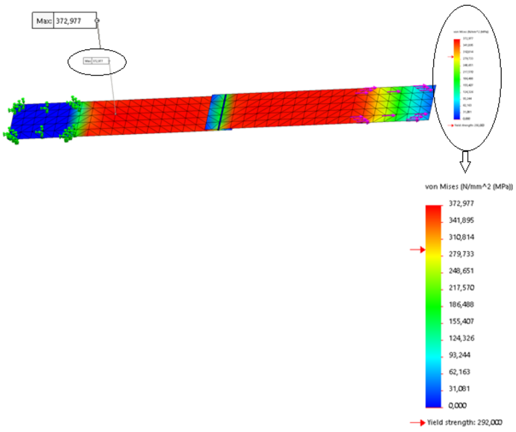


Figure 10. Example of FEM analysis for a pair of TL -TL materials

4 Use of FEM analysis for glued joints

Knowledge of the behavior of glued joints is essential for their subsequent application in practice. For effective prediction of the properties of glued joints it is necessary to use suitable tools allowing to accurately model various modes of failure that may occur in the structure. The failure of glued joints includes the area from the beginning of loading to the initiation of the crack, followed by the area of development of the failure.

Table 3. Simulation results for sheet metal plates combinations

Combination of materials (fixed – pulled sheet)	Loaded by Fe for pulled sheet (MPa)	Loaded by Fe for fixed sheet (MPa)	Loaded by Fm for pulled sheet (MPa)	Loaded by Fm for fixed sheet (MPa)	Force when weld breaks max F (N)
TL-TL	295.967	295.967	372.977	372.977	7359.5429
TL-HX	419.625	295.967	479.427	378.068	7360.4713
TL-HCT	350.701	295.967	662.886	378.068	7360.0309
TL-DC	199.677	295.967	331.443	378.068	6492.8157
HX-HX	419.625	419.625	479.427	479.427	9332.8498
HX-HCT	350.701	419.625	662.886	479.427	9332.8498
HX-DC	199.677	419.625	331.443	479.427	6492.8157
HCT-HCT	350.701	350.701	662.886	662.886	12905.6504
HCT-DC	199.677	350.701	331.443	662.886	6492.8157
DC-DC	199.677	199.677	331.443	331.443	6452.6495

According to the gained results, it is quite noticeable that force until weld break, for same material pairs, is quite similar to the computed theoretical force for a given material (obr. 10). The theoretical force is greater than analysis one. This variance can be caused by the difference in theoretical model, which was computed in a way that did not included torque, just linear propagation. In simulated model however, this additional torque was taken into account, which lowered the final value.

For the other combinations of materials the force was heavily reduced by weakest one from the pair, which was carried out across all simulated pairs, hence TL-DC, HX-DC, HCT-DC have the same value (Table 3).

The possibility of numerical simulation of the glued joint is the main requirement for its successful design. If a suitable numerical method was found, it would be possible to replace a large part of the glued joint experiments with this simulation. This would lead to a reduction in the times involved in the development, production and production cost of the product.

The simpler tools offered by FEM analysis allow you to model only the area from the beginning of the load to the initiation of damage. The principles of linear elastic fracture mechanics apply in this area. The behavior in this area is described by the cohesive stiffness of the adhesive layer. The failure initiation state occurs at a critical value of the stress at the crack front. In the FEM model, this state describes the tension between the nodes of an idealized adhesive layer caused by their critical displacement and critical load.

Elements commonly available in FEM analyzes can be used to idealize the adhesive layer. Their behavior is described in terms of material parameters, which in some cases can be obtained from glue producers, but more often it is necessary to find out more difficult by means of experiments. Specifically, the adhesive layer can be replaced by contact, 3D elements, 2D elements, a linear spring system, or simply replacing the adhesive, such as the SSG element in Siemens NX or the TIE element in Abaqus.

The first step is to create a CAD model. This model is then converted into a preprocessor, which converts the geometric model into the form necessary for the calculation itself. In this phase, the main task is to create an adequate computer network and to define the initial conditions correctly. The preparation of the whole calculation model follows the rules that each company creates itself and must be strictly observed. The rules are set to achieve a compromise between computational complexity and result accuracy.

The next step is to load the file into the solver and start the calculation itself. The calculation is started using the command line and follows the mathematical operations described above. The results are written to files during the calculation.

The last step is to load and process the results in the postprocessor. The postprocessor allows viewing the simulated process, plotting acceleration, stress, strain and many other variables depending on the selected variable.

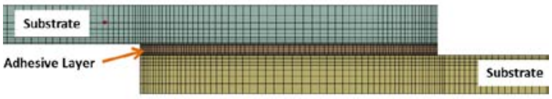


Figure 11. 2D plain strain finite element model of bonded joint

In recent years, models using the so-called cohesive joint model have been used in the research of glued joints. The cohesive Model can be used to model adhesives, bonded surfaces, seal models, patches, or delamination processes (Fig. 11). The cohesive model must be implemented in the numerical model of FEM analysis.

4 Conclusion

The effort of the car manufacturer is to produce cars of the lowest possible weight, which in practice means a reduction of materials of different thickness and quality, whether metallized or unplated, but also for the connection of ferrous and non-ferrous metals. Their use in the automotive industry opens up new opportunities for designers. These consist in the optimal use of the properties of different types of sheets, which can be combined into one unit and thus affect the strength, stiffness or corrosion resistance and resistance to chemical aging.

One of the many conditions is that the car must guarantee a prescribed level of passive safety, which is tested under predetermined conditions. At present, we are still looking for possibilities and technologies that would mean cheaper, faster and more accurate production of cars, while maintaining the conditions and criteria required by us. These technologies undoubtedly include computer design of cars. Everything is done on computers from designing, designing individual components, to demanding strength calculations and simulating vehicle barrier tests. In all calculations and simulations, the aim is to bring the computational model to reality as much as possible. Simulation by finite element method of the glued and welded joints allows to reduce the time for product development, production and production costs.

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