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Research

DESIGN AND SIMULATION OF A HEAVY-DUTY VEHICLE STEERING COMPONENT BY ANALYTIC AND FEA METHOD

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ABSTRACT

All vehicles need a steering system for safe driving. Drag link is a crucial component of the steering system in heavy commercial vehicles because it allows us to travel safely by transmitting the rotational movement from the arm of the pitman to the axle of the wheel linearly. The drag link used in a vehicle should be manufactured from materials that are resistant to variable loads depending on the vehicle's operating conditions. Furthermore, the rod arms must fulfill the expected function in tight spaces in the vehicle package data, and be designed in different bends and geometries depending on the regulation conditions they are subject to. In this study, different tube raw materials such as; St37-2, St 52-3, and P460 N were selected, and bending strengths calculated under various loading conditions. Finite Element (FE) models created, analyses performed, and the effects of different loads on the drag link were evaluated. Obtained results from the Finite Element Analysis (FEA) were compared with each other. Suitable material was selected based on analytic and FEA studies.

Keywords: Design of drag link, Finite element analysis, Buckling strength, Steering system.

1. INTRODUCTION

All vehicles must have the steering system for safe driving, as shown in Figure 1. Drag links, an essential component of the steering system in heavy commercial vehicles, are generally made up of hollow tubes with both ends connected by ball joints. They are critical for the vehicle to travel safely by transmitting the rotational movement from the pitman arm linearly to the axle of the wheel. The drag links used in a vehicle must be manufactured from materials resistant to variable loads coming from the vehicle, depending on the operating conditions. Furthermore, drag links are required to perform the expected function in narrow spaces in the vehicle package data and to be designed in different bends and geometries depending on the regulation requirements [1].

Drag link is produced by making different bends to the tube materials used in order to obtain the geometry suitable for the design. Usually, buckling failure may occur in these areas of the drag link due to different compressive loads occurring in road conditions. The buckling and deflection are also important parameters for the rod subjected to compression and tension due to the force based on the road [2].

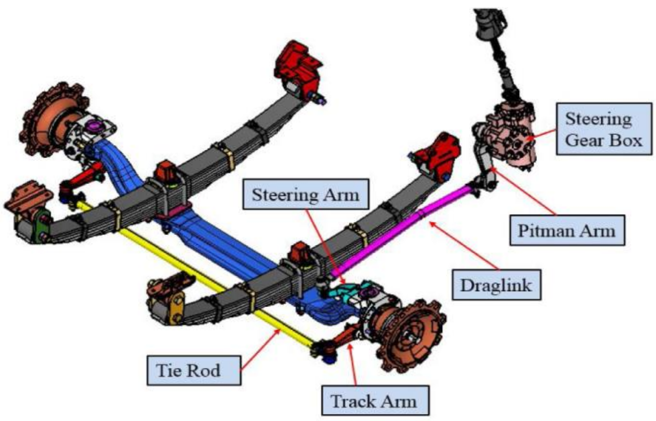

Figure 1. The schematic diagram for steering system & linkages [3]

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The buckling load calculation of the drag links as a critical part of driving system is crucial. Theoretical calculations take a long time due to the complex geometry of the rods in the design phase. On the other hand, verification tests performed to designed parts usually are costly and take a long time. Therefore, the Finite Element Method (FEM) used in determining the stresses and deformations to which the rods are exposed provides more accurate results in a short time [4]. Ganesh et al. (2014) studied the ford car steering rod's structural analysis and evaluated its performance [5]. Winklberger et al. (2018) studied on fatigue strength and weight optimization of the aircraft rods by using FEM. As a result of the study, it was determined that the tooth position had more effect on fatigue strength than tooth length [6]. Doke et al. (2016) calculated buckling strength for a drag link and analyzed its tubes against compressive loads. He also investigated the relations of various design parameters with buckling strength, which is useful for optimizing design parameters [7]. Kim et al. (2011) optimized the rod weight using the Al6082M aluminum alloy as a rod material [8].

Sener (2016) used road data collected from rods in order to be able to extract road characteristics. In his study, about 50 road routes and some rough road fatigue characteristics were acquitted with a Light Commercial Vehicle (LCV) equipped with sensors [9]. Neelakrishnan et al. (2017) analyzed the steering characteristics of an All-Terrain Vehicle (ATV) to improve the maneuverability of the vehicle by designed steering gearbox upright [10]. Gadher et al. (2017) studied the design and manufacturing of steering systems to acquire maximum Ackerman angles in the proposed steering system [11]. Aravind Kumar et al. (2016) designed to different types of drag links. They performed buckling analysis and rig tests to tube in a tube and typically designed drag links, results obtained from CAE and buckling test rig shows that the buckling load of the drag link can be improved by reinforcing the buckling zone [12]. Yaşar and Bircan (2015) examined optimum design parameters of the car chassis by taking into account different chassis types, dimensions, and materials to achieve minimum weight and deflection. They designed and analyzed for various geometries and materials. Also, they optimized the consequences of the analysis by the Taguchi method with Minitab. When studies are examined, FEM is used in applications such as weight and cost reduction, part optimization, and life predictions. It provides to take advantage of product development processes and design verification tests, also reduces cost by saving time and raw material [13, 14].

In this study, different tube materials made of ST37-2, ST52-3, and P460 N were described as calculation of buckling strength. Also, drag link tubes were analyzed in different compressive loads of 20, 25, and 40kN. The effects of various loading parameters on buckling strength were evaluated. Each value obtained from FEA results was compared. Analytical calculations were repeated to determine proper drag link for the design parameters.

2. MATERIAL AND METHOD

2.1. Design and Calculation of the Drag Link

The steering arm's buckling force is the force generated at the pitman arm's end because of turning forces in dynamic conditions, and equal to the exposed buckling load of the drag link tube. For the design of drag link against buckling loads, buckling strength must be more than the force generated at pitman arm end. The drag link used in a heavy vehicle can be illustrated in Figure 2.

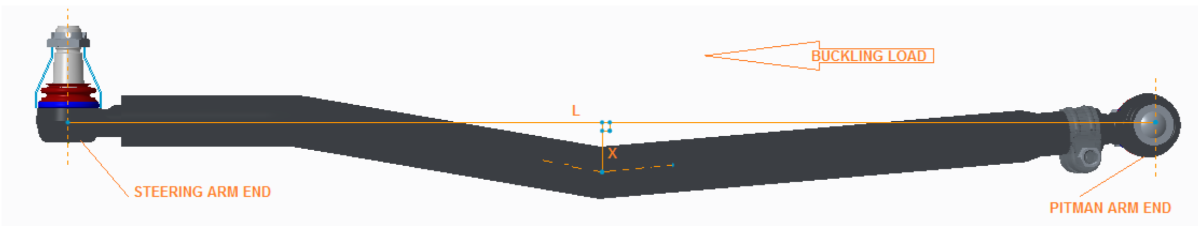

Figure 2. Buckling load on drag link tube

Crippling or Buckling Load (FB) can be expressed by using Rankine's formula for the drag link. It gives the ultimate load that the column can bear before failure. If the column is short (L<20D), the calculated load will be known as a crushing load. However, if L is longer than 20D (L>20D), the load will be buckling or crippling. The buckling formula is given in equation 1 (in case of long column):

$$F_B = \frac{(\sigma \times A)}{\left(1+\frac{L^2}{6250\times k^2}+\frac{(X\times Y)}{k^2}\right)} \quad (1)$$

Where σ refers to the yield strength of the tube material, changes depending on types of material, the radius of gyration (k) is defined as the distance from the axis of rotation to a point where the body's total mass is supposed to be concentrated, so the moment of inertia about the axis may remain the same. Simply, gyration is the distribution of the object; k is found as 15.70 mm. Moment of inertia (I) is the capacity of a cross-section to resist bending [15]. It is calculated as $204.442*10^3$ Kg-mm^4. Section modulus, Y is equal to 25 mm ($D_o/2$) and its area, A is 829.71 mm^2. Axis Height (X) is a distance between the centerline of the bent tube and the axis line drawn between the two end rods (L), as shown with the perpendicular line in Figure 2. L refers to the distance from center to center. The tube inner and outer diameter are illustrated as D_o and D_i, and these are 50 mm and 38 mm, respectively. They are critical for calculating the moment of inertia, its area, and section modulus. Offset of drag link tube, X is 59 mm. The design parameters of the tube structure used in the drag link were shown in Table 1.

The most critical parameter is the mechanical properties of the tube material when calculating buckling strength in the design of drag links. These tube materials are the most commonly used materials for drag link. Seamless tubes are preferred in automotive applications because of their durability. Buckling strength of tube materials are found by using Rankine's formula for drag link. St 37-2 seamless tube is one of the commonly used and cheapest tube materials on the market. However, it has about 30-35% lower mechanical strength than St 52-3 in terms of strength. The buckling strength of the St 37-2 seamless steel tube was calculated as 25.3 kN. Similar calculations performed for P460 N and St 52-3 seamless steel tube materials as 38.2 and 49.5 kN, respectively.

Table 1. Design parameters of tube structure used in drag link

Parameters	Unit	Value
Outer Diameter, D_o	(mm)	50
Inner Diameter, D_i	(mm)	38
Distance From Center to Center, L	(mm)	1059
Axis Height, X	(mm)	59
The radius of Gyration, K	(mm)	15.70
Moment of Inertia, I	(Kg-mm^4)	$204.442 * 10^3$
Section Modulus, Y	(mm)	25
Area, A	(mm^2)	829.71
Calculated Buckling Strength	(kN)	25.3 For St 37-2 38.2 For St 52-3 49.5 For P 460 N

Tube materials of the drag links exhibit different properties and mechanical performance depending on the amounts of their chemical composition. In particular, elements such as C and Mn in the structure of steels directly affect the strength of the structure. Chemical compositions of tube materials used in the study are given in Table 2.

Table 2. Chemical compositions for tube materials

Content (%)	St37-2	St52-3	P460 N
C	0.17	0.22	0.20
Si	0.35	0.55	0.60
Mn	1.40	1.60	1.70
P	0.05	0.05	0.03
S	0.05	0.05	0.042

Seamless tube material of St 52-3 does not meet the target strength values in the drag link design, P460 N tube material may be preferred. This material has 1.3 times higher strength than St 52-3 tube material. However, it affects product costs significantly since it is much more expensive than St 37-2 and St 52-3 tube materials. The mechanical properties of tube materials are tabulated in Table 3.

Table 3. Mechanical Properties of Tube Materials

Mechanical Properties	St 37-2	St 52-3	P460 N
Tensile Strength (MPa)	460	570	680
Elongation at Fracture (%)	25	21	19
Yield Strength (MPa)	235	355	460

3. ANALYSIS OF BUCKLING STRENGTH FOR DRAG LINK

When the solid model is to be analyzed by using the FEM, the model is simplified by removing the assembly parts, which can not affect the result of the analysis. In this way, the solution time of the mathematical model is decreased. In the analysis, drag links with three different tube materials as St 37-2, St 52-3, and P460 N were compared. Proper meshing operation on geometry is an essential parameter for reducing errors in numerical calculations. For the geometries that evaluated in this study, tetrahedral elements performed better results and reduced mathematical error. The drag link's structural meshing can be seen in figure 3. After the properties were assigned and mesh operation was performed, the boundary condition of the drag link was applied as fixing from one of the housings and 40, 25, 20 kN compressive load from the other.

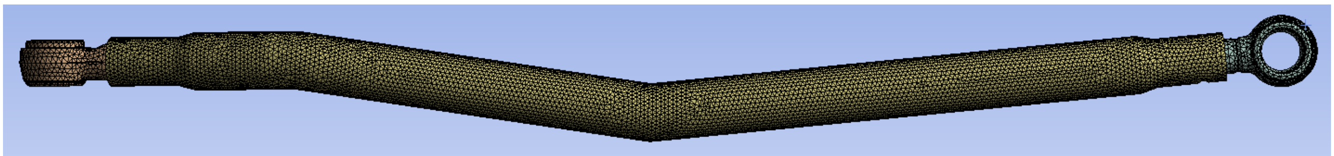

Figure 3. The structural meshing of the drag link

On the other hand, mesh dependency is very critical in FEA. Therefore, the simulations are repeated for different mesh densities for St52. The properties of the mesh and the resulting maximum stresses are calculated by changing the mesh sizes iteratively. Convergence and mesh independence for FEA is given in Table 4. The element quality and deviation values decrease as the mesh size decreases. Furthermore, element quality is increased by decreasing the mesh size and at the maximum for 4 mm mesh size. Decreasing the mesh size to less than 4 mm increases the number of elements and changes the observed maximum stress negligibly. The change in the maximum stress according to the number of elements is plotted based on the values in table 4. Mesh independence is shown in Figure 4 with the graph of maximum stress – number of element in mesh. Adding elements increases the solving time. At some point, more items with without improvement in the solution increase the solution time. The improvement made after this point is an inefficient implementation of FEA.

Table 4. Convergence & Mesh Independence for FEA

Mesh Size (mm)	Max. Stress (MPA)	Number of Nodes	Number of Elements	Element Quality (Average)	Standard Deviation (%)
20	329.03	40291	24055	0,71326	0,20608
15	346,95	43750	25774	0,72106	0,19294
10	356,4	53484	30629	0,75161	0,17832
5	368,89	149109	88759	0,79044	0,13503
4	370,76	223574	134477	0,83192	0,12179
3	373,74	445132	278533	0,80673	0,11471
2	377,79	1341250	887613	0,8261	0,1024

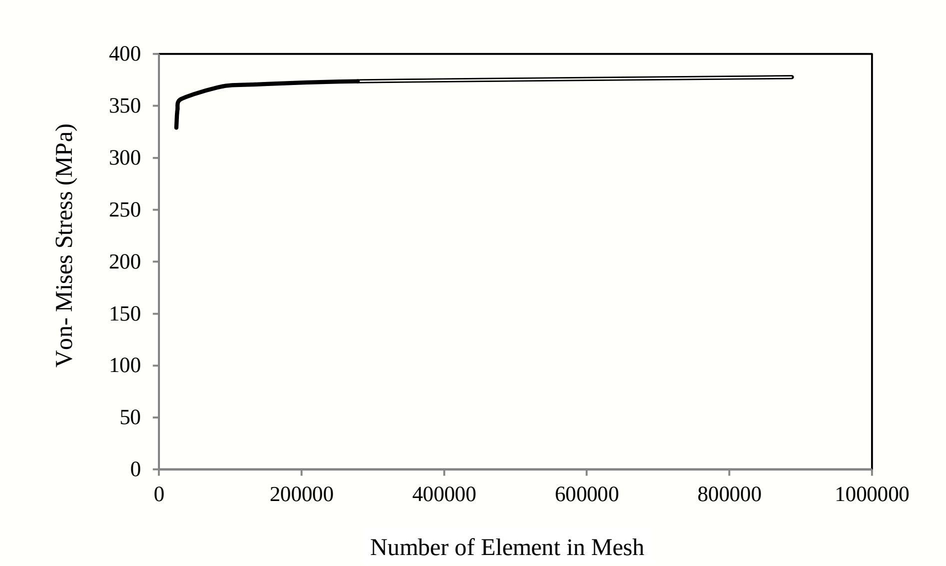

Figure 4. The maximum stress-number of element in mesh

4. RESULTS AND DISCUSSION

The drag link, a steering part of a heavy commercial vehicle, was designed using 3D parametric software Creo 3.0, and the analyses were conducted using ANSYS via the FEA method. The development and application of the FEA considerably reduce the time and effort required for the steering components design process [16]. Designed drag link geometry was evaluated by defined raw materials of the tube with different loads. The maximum buckling load that the tube material can withstand is found by calculating the buckling strength. The maximum buckling load refers to the load value that the drag link can withstand without plastic deformation. As a result, the stress at the bending point of the tube for 40 kN load is close to the yield point of the St 52-3. Therefore, proposed drag link should be made by P 460 N has higher buckling strength for compressive loading 40 kN and more. Because, loading 40 kN or more is risky for St 52 tube material, and loadings over than 38.2 kN exceed to elastic limit of the St 52-3 tube material. On the other hand, St 37-2 tube material is unsafe for over 25 kN loading. Design calculations and FEA provide an advantage in material selection and product costs. The drag link should be designed with the optimum material by considering the loads which are exposed to.

For loading 40 kN, Von-Mises stress distributions of St 37-2, St 52-3, and P460 N tubes were illustrated in Figures 4, 5, 6 and 7, respectively. Stress concentration on tube has occurred at tube bending areas as expected. 377.4 MPa was calculated as highest Von-Mises stress on the geometry, and 1.218 was found as a minimum safety factor for P460 N. Also, 360.81 MPa was calculated as highest Von-Mises stress on the geometry, and 0,983 was found as a minimum safety factor for St 52-3. The stress at the bending point of the St 52 tube under 40 kN load is over its yield point. Therefore, this load is critical for St 52 tube material. Also, the St 37-2 material is completely deformed at this loading, which is 55% higher than the bending strength calculated, and St 37-2 is not recommended for a drag link with such geometry. Von-Mises stress occurred on St 37-2 is 359.52 MPa, and safety factor is 0.653. Both tube materials have similar stress values for the same loading conditions. This shows that this drag link should be made by P 460 N, has higher buckling strength for 40 kN compressive loading.

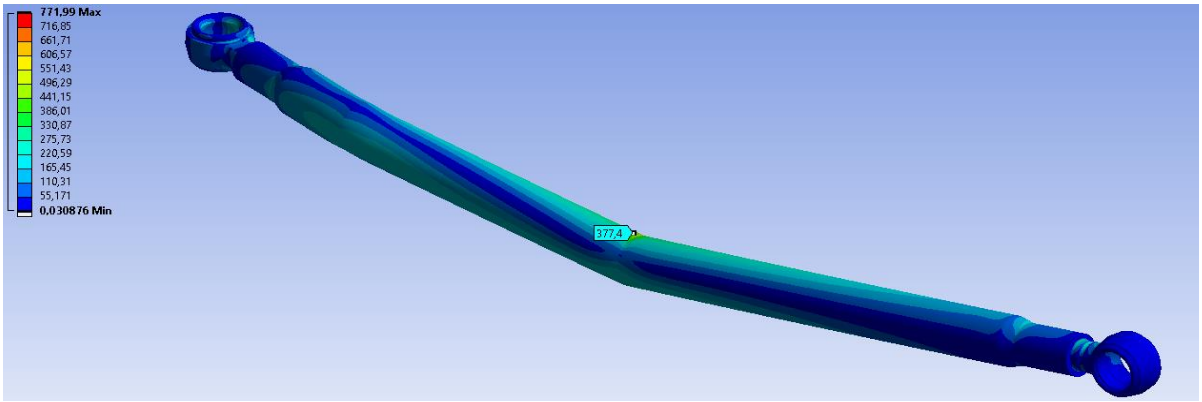

Figure 4. Stress Distribution of the P460 N Tube for 40 kN (Von-Mises)

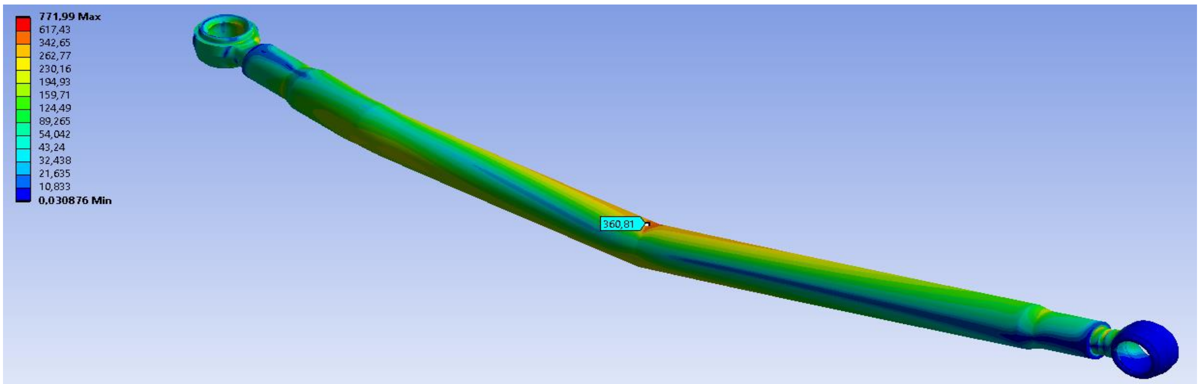

Figure 5. Stress Distribution of the St 52-3 Tube for 40 kN (Von-Mises)

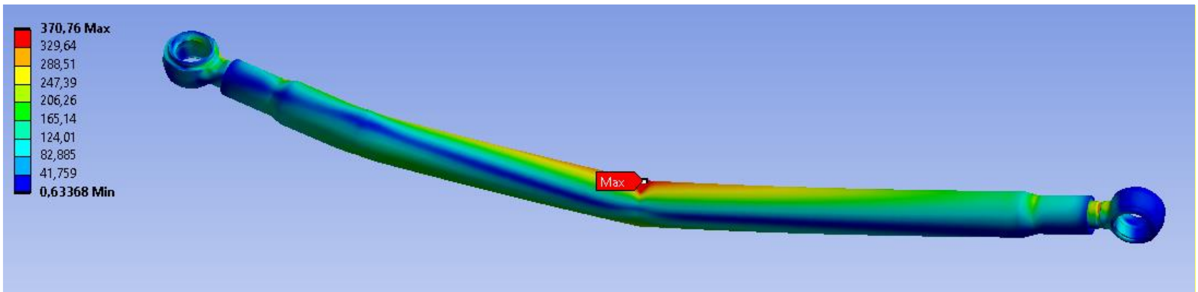

Figure 6. Stress Distribution of the St 52-3 Tube for 40 kN (Von-Mises) (mesh size 4 mm)

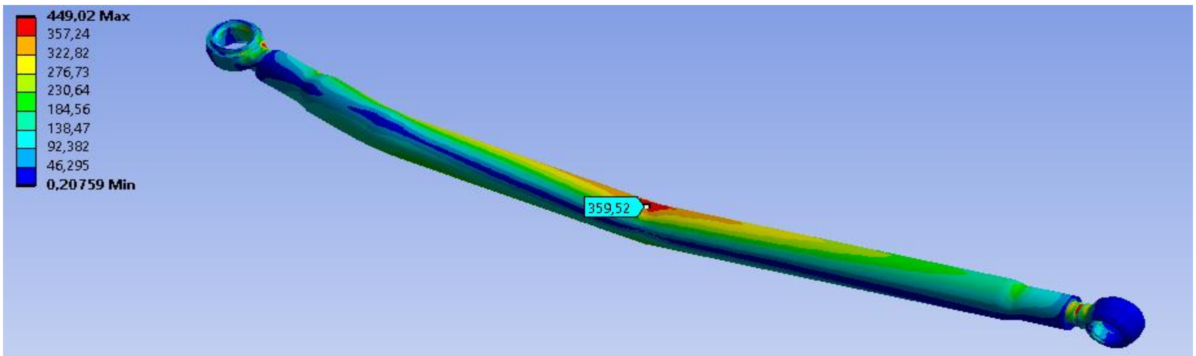

Figure 7. Stress Distribution of the St 37-2 Tube for 40 kN (Von-Mises)

The highest stress for 40 kN load were seen as 771.99 MPa when the stress distribution obtained from the analysis examined. However, sudden stress increases were observed in some mesh elements. This is called the singularity. In the analysis, the critical stresses are occurred on the tube bended region, these stresses due to singularity are ignored.

In addition, the mesh independence was studied and the analysis was repeated for the st52-3 tube material. Stress distribution of the St 52-3 Tube for 40 KN was shown in Figure 6. With the improvement of the mesh size and properties, singularities were eliminated, and the maximum stress was observed again in the tube bended region. In the repeated analysis, very little change was observed in the maximum stress value of the tube material and this difference of approximately 2.8% was neglected as it would not significantly change the overall results.

For loading 25 kN, analyses of St 37-2, St 52-3, and P460 N tubes were performed and von-Mises stress distributions were investigated. The stress concentration for 25 kN is approximately 35% lower than 40 kN, and 2.067 was found as a minimum safety factor for P460 N. Also, similar Von-Mises stress on the geometry and 1.532 was found as a minimum safety factor for St 52-3. This stress at the bending point is not critical, and also both of these tube materials are safe for 25 kN compressive loading. Stress concentration on St 37 was calculated as 232.12 MPA. It is close to its yield strength, and the minimum safety factor for St 37 was calculated as 1.012. Therefore, 25 kN loading is safe for all raw material, but St 37-2 tube material is unsafe if 25 kN loading is exceeded for proposed design.

As a result of the analyses carried out for 20 kN tubing materials, von- Mises stress on the part decreased depending on the loading. For loading 20 kN, Von-Mises stress distributions of drag links produced with P460 N, St 52-3, and St 37-2 tube materials were obtained similar to other loadings. The stress concentration decreased by 50% compared to the initial loading (40 kN) due to the reduction of the load. Minimum safety factors for P460 N, St 52-3, and St 37-2 were found as 2.486, 1.936, and 1.197. Stress occurred at the bending point is not critical, and all of these materials are safe for 20 kN compressive loading. If one of these three materials is preferred for the 20 kN loading value, safe drag link designs with 1.2 safety coefficient desired from the steering system parts can be realized. In Figure 8, Von-Mises stress-force and safety factor of the tube materials are seen comparatively.

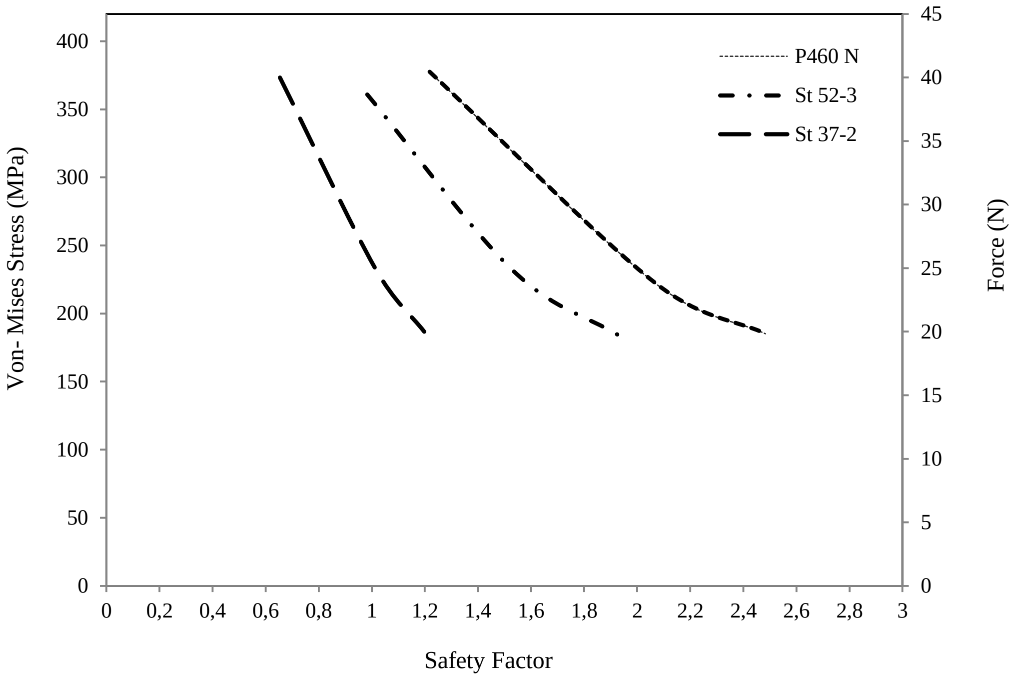

Figure 8. Von-Mises Stress-Force and Safety Factor of the tube materials

Analytical calculations are carried out for the drag link and the total stresses in the part are calculated from the normal stress and bending stresses. Theoretically calculated stress values for geometry of drag link are 183, 229 and 366 MPA for 20, 25 and 40 KN, respectively. Comparison of analytical calculations and FEA results was given in Table 5. When these calculations are examined, the calculated and analysis results match each other. Generally, error rates are mostly in the range of 0,21-3,75%, and FEA results with an error of less than 5% are acceptable.

Table 5. Comparison of Analytical Calculations and FEA Results

Tube Material	Loading (KN)	Calculated Theoretical Stress (MPA)	FEA results (MPA)	Error (%)
St 37-2	40	366,16	359,52	1,81
St 52-3	40	366,16	370,76	1,25
P460 N	40	366,16	377,4	3,06
St 37-2	25	228,85	232,12	1,42
St 52-3	25	228,85	223,69	2,25
P460 N	25	228,85	220,26	3,75
St 37-2	20	183,08	179,80	1,79
St 52-3	20	183,08	177,22	3,20
P460 N	20	183,08	183,47	0,21

5. CONCLUSION

In this study, the buckling strength of proposed drag link in a heavy vehicle for different tube materials of P460 N, St 52-3, and St 37-2 was calculated analytically. The effects of various bending parameters on buckling strength were evaluated. It was suggested that the drag link should be made by P 460 N, with higher buckling strength, compressive loading 40 kN, and more.

20, 25, and 40 kN compressive loads were applied to the drag link model in FEA. The stress at the bending point of the tube for 40 kN load is close to the yield point of the St 52. Therefore, designed drag link should be made by P 460 N, which has higher buckling strength for compressive loading 40 kN and more. Because, loading 40 kN or more is risky for St 52 material, and loadings over than 38.2 kN exceed to elastic limits of the tube material. All suggested materials are safe for 20 and 25 kN loading, but St 37 material should not be selected for loadings over 25 kN. If one of these materials is preferred for the 20 kN loading based on light duty vehicles, safe drag link designs with 1.2 safety factor desired. Consequently, the material should be selected taking into account the criteria of reliability and affordability for a drag link (or another steering component) with optimum performance in a heavy-duty vehicle.

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