International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

AUTOMOTIVE SUSPENSION CONTROL ARM

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ABSTRACT

The lower control arm is one of the most heavily loaded members of a passenger car suspension. It connects the wheel knuckle to the vehicle body through a ball joint at the outer end and two rubber bushings at the inner end, and it carries the longitudinal, lateral and part of the vertical forces generated at the tyre contact patch during braking, cornering and travel over uneven roads. A failure of this component leads to a sudden loss of wheel control, so its strength, stiffness and fatigue behaviour must be established with care before it is manufactured. At the same time, the arm is part of the unsprung mass of the vehicle, and any reduction in its weight improves ride comfort, road holding and fuel economy.

This work presents the design and analysis of a front lower control arm for a MacPherson strut suspension of a compact passenger car with a kerb mass of about 1,200 kg. The geometry of the arm was modelled in SolidWorks using hard points taken from a typical front suspension layout, and the model was transferred to ANSYS Workbench for static structural, modal and fatigue analysis. Three load cases were studied, namely braking, cornering and a combined pothole event, and the combined pothole case with 6.5 kN longitudinal, 5.8 kN lateral and 3.5 kN vertical force at the ball joint was found to govern the design.

Five candidate materials were compared under identical geometry, mesh and boundary conditions: structural steel, forged alloy steel AISI 4340, aluminium alloy 6061-T6, aluminium alloy 7075-T6 and titanium alloy Ti-6Al-4V. For each material the equivalent von Mises stress, total deformation, factor of safety based on yield strength, mass and first natural frequency were recorded. Structural steel reached a maximum stress of 186.4 MPa with a factor of safety of only 1.34, while aluminium 7075-T6 reached 182.9 MPa with a factor of safety of 2.75 at a mass of 1.22 kg against 3.42 kg for the steel arm.

Based on this comparison, aluminium alloy 7075-T6 was selected, and the arm was refined by adding lightening pockets in the web and a stiffening rib along the inner edge, guided by the low-stress regions seen in the contour plots. The refined arm has a mass of 1.08 kg, a maximum von Mises stress of 211.6 MPa near the front bushing neck, a total deformation of 1.94 mm and a factor of safety of 2.38. This represents a mass reduction of 68.4 percent compared with the structural steel baseline.

Received: 05-10-2026 | Accepted: 08-11-2026 | Published: 17-11-2026

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I. INTRODUCTION

The suspension system of a vehicle keeps the tyres in contact with the road, isolates the occupants from road disturbances and controls the motion of the wheels relative to the body. In the MacPherson strut arrangement, which is used on the front axle of most small and medium passenger cars, the strut carries most of the vertical load while the lower control arm locates the bottom of the wheel knuckle. The arm therefore controls the camber and track of the wheel and transmits the forces produced when the vehicle brakes, accelerates, turns or strikes a road irregularity.

Because the lower control arm sits between the wheel and the body, it is subjected to a combination of bending, torsion and axial forces that change continuously during driving. Large impact loads occur when a wheel enters a pothole or strikes a kerb, and repeated smaller loads occur over every kilometre of normal driving. A control arm must therefore be strong enough to resist the occasional severe load without permanent deformation, stiff enough to hold the wheel geometry, and durable enough to survive millions of load cycles. Cracks that develop near the bushing housings or the ball joint seat are a known cause of suspension failure in service.

Traditionally, control arms have been made from pressed or forged steel, which is cheap and strong but heavy. Vehicle manufacturers now place great importance on reducing unsprung mass, because a lighter wheel assembly follows the road more closely and transmits less shock to the body. Aluminium alloys, forged alloy steels and, in high-performance vehicles, titanium alloys have all been used to make lighter arms. Choosing among these materials requires a reliable way to predict stress, deformation and life for each option before tooling is made, and this is where computer-aided design and finite element analysis are useful.

The present work develops a three-dimensional model of a front lower control arm, applies loads representing braking, cornering and a pothole impact, and analyses the arm in ANSYS Workbench with five candidate materials. The results are compared on the basis of stress, deformation, factor of safety, mass, natural frequency and fatigue life, and the most suitable material is then used in a refined lightweight design. The objective is to arrive at a control arm that meets the strength and stiffness requirements with the lowest practical mass, using a procedure that a design engineer can repeat for similar components.

II. LITERATURE SURVEY

Studies on suspension components consistently describe the lower control arm as a safety-critical part whose design is governed by a small number of severe load events rather than by normal driving. Investigations of service failures have shown that cracks usually start at geometric transitions, such as the neck between the arm body and the bushing housing, the region around the ball joint seat, and the edges of holes or slots in pressed arms. These locations combine high nominal stress with stress concentration from sharp fillets or abrupt changes in section. Researchers have therefore recommended generous fillet radii, smooth section transitions and careful control of surface finish at these points. Several authors have also pointed out that the loads acting on the arm must be represented realistically, since an analysis based on a

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single vertical load underestimates the bending and torsion produced by combined braking and cornering forces.

A large body of work has applied finite element analysis to control arms and similar suspension links. In most reported studies the geometry is modelled in a commercial CAD package such as SolidWorks or CATIA, imported into ANSYS or a comparable solver, and meshed with tetrahedral elements of second order. The inner bushing locations are usually treated as fixed or as cylindrical supports, and the wheel loads are applied at the ball joint. These studies report that the maximum equivalent stress almost always appears near the inner bushing housings, which agrees with field observations. They also show that refining the mesh locally at fillets has a strong influence on the predicted peak stress, and that a mesh convergence study is needed before the results can be trusted for design decisions.

Material substitution has been examined widely as a route to lighter suspension arms. Comparisons between structural steel, forged alloy steels, aluminium alloys and composite materials have been reported under identical geometry and loading. A general finding is that the stress pattern changes very little between materials when the geometry is fixed, because the arm is statically determinate in its main load paths, while the deformation increases in inverse proportion to the elastic modulus. Aluminium alloys therefore deflect about three times as much as steel for the same shape, but their much lower density allows large mass savings. High-strength alloys such as 7075-T6 have been found to give a good balance between yield strength and weight, while titanium alloys provide the highest safety margin at a considerably higher material and machining cost.

Modal and fatigue analyses have been added to static studies in more recent work. Modal analysis is used to confirm that the natural frequencies of the arm lie well above the frequencies of road excitation and wheel hop, which are generally below about 25 Hz for passenger cars, so that resonance does not amplify the service loads. Fatigue studies have applied stress-life methods with mean stress correction, typically the Goodman relation, to estimate the number of load cycles to crack initiation at the critical locations. Researchers have noted that aluminium alloys do not have a true endurance limit, so a finite design life must be specified and checked. Studies that combined static, modal and fatigue results reported more balanced designs than studies that relied on static stress alone.

Shape refinement and optimisation form the most recent direction in this area. Topology optimisation has been used to identify regions of the arm that carry little load, so that material can be removed by pockets or cut-outs, and the resulting concepts have been converted into manufacturable forged or cast shapes. Reported mass reductions range from moderate values for steel arms to more than half the original mass when a change to aluminium is combined with shape refinement. Authors have emphasised that every refined shape must be re-analysed for strength, stiffness and natural frequency, because removing material raises local stresses. The present work follows this sequence by comparing materials first, selecting the most suitable alloy, and then refining the shape using the stress distribution obtained from the analysis.

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III. SYSTEM ANALYSIS

The design problem is to obtain a front lower control arm that carries the loads transmitted from the wheel without yielding, holds the wheel geometry within acceptable deflection and survives repeated road loading, while keeping its mass as low as possible. The arm is connected to the body by a front and a rear rubber bushing and to the wheel knuckle by a ball joint, and these three points define its kinematic role in the suspension. Three load cases are considered: a braking case with 1.0 g deceleration, a cornering case with 0.9 g lateral acceleration and a combined pothole case with 6.5 kN longitudinal, 5.8 kN lateral and 3.5 kN vertical force at the ball joint. The required outputs are the equivalent von Mises stress, total deformation, factor of safety on yield, mass, first natural frequency and fatigue life. The design targets are a factor of safety of at least 2.0 under the governing load, a deflection at the ball joint below 2.5 mm and a first natural frequency far above road excitation.

Existing System

In conventional practice, a control arm is first sized by hand calculation, treating it as a simple beam or a pin-jointed frame loaded at the ball joint and supported at the bushings. Such calculations give nominal bending and axial stresses but cannot represent the curved shape of the arm, the change of section along its length or the stress concentration at the bushing necks and the ball joint seat. To cover this uncertainty, designers use large safety factors, which leads to heavy arms. The design is then confirmed by making prototypes and testing them on a rig or in the vehicle, often with strain gauges at chosen points. If a prototype cracks or deforms, the shape is modified and a new prototype is made, so each iteration requires new tooling, machining and test time. Comparing alternative materials in this way is slow and expensive, and only a few options can be evaluated before production deadlines are reached. Information on stresses away from the gauge locations is also not available.

Disadvantages of Existing System

- Hand calculations treat the arm as a simple beam and ignore its true curved geometry.
- Stress concentration at the bushing necks and ball joint seat is not captured accurately.
- Large safety factors are needed to cover uncertainty, which makes the arm heavy.
- Each design change requires a new physical prototype with tooling and machining cost.
- Rig and vehicle testing take considerable time for every design iteration.
- Only a few candidate materials can be compared within a practical budget.
- Strain gauges measure stress only at a few chosen points on the component.
- Natural frequencies and resonance risk are not checked during early sizing.
- Fatigue life is estimated late, often only after a prototype has failed.
- Low-stress regions where material could be removed are not identified clearly.

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Proposed System

The proposed approach uses a computer-aided design and finite element analysis workflow to evaluate and refine the control arm before any physical part is made. The arm is modelled in SolidWorks with its bushing housings, ball joint seat, web and flanges defined from suspension hard points, and the model is imported into ANSYS Workbench. Engineering data for structural steel, AISI 4340, aluminium 6061-T6, aluminium 7075-T6 and Ti-6Al-4V are assigned in turn while the geometry, mesh and loads stay unchanged, so the results are directly comparable. Static structural analysis gives the von Mises stress, total deformation and factor of safety for each load case, modal analysis gives the natural frequencies, and the fatigue tool estimates the life at the critical locations. The material that best meets the targets is then used in a refined geometry with web pockets and an edge rib placed according to the stress contours, and the refined arm is analysed again to confirm that all targets are still satisfied.

Advantages of Proposed System

- The true three-dimensional geometry of the arm is represented in the analysis.
- Peak stresses at fillets, bushing necks and the ball joint seat are located precisely.
- Five materials are compared under identical geometry, mesh and loading conditions.
- Braking, cornering and pothole load cases are evaluated without building prototypes.
- Deformation at the ball joint is checked against the wheel geometry requirement.
- Modal analysis confirms that natural frequencies are far from road excitation.
- Fatigue life is estimated early in the design rather than after a failure.
- Low-stress regions guide the placement of pockets and ribs for weight reduction.
- Mass of the arm is reduced by 68.4 percent compared with the steel baseline.
- The workflow can be repeated for other suspension links with little change.

IV. METHODOLOGY

The methodology followed six stages. First, the suspension hard points, overall envelope and load cases were defined from the layout of a compact car front suspension with a kerb mass of about 1,200 kg. Second, the arm was modelled in SolidWorks as an I-shaped forged section with a front bushing housing of 45 mm bore, a rear vertical bushing housing and a 38 mm ball joint seat, and fillets of at least 5 mm were added at all transitions. Third, the model was imported into ANSYS Workbench and material properties were assigned from the engineering data library. Fourth, the arm was meshed with ten-node tetrahedral elements, and a convergence study at 5, 4, 3, 2 and 1.5 mm element size showed a change in peak stress of 1.4 percent between the last two sizes, so a 2 mm mesh with 146,820 nodes and 92,415 elements was adopted. Fifth, cylindrical supports were applied at the bushing bores and the wheel forces at the ball joint seat. Sixth, the static, modal and fatigue solutions were solved and post-processed.

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SYSTEM ARCHITECTURE

The design workflow is arranged as a sequence of stages with a feedback loop. The input stage collects the vehicle data, suspension hard points and the three load cases. The CAD modelling stage in SolidWorks produces the parametric solid model of the arm, which is passed to ANSYS Workbench through a neutral geometry file. The material stage draws Young's modulus, Poisson's ratio, density, yield strength and fatigue data for the five candidate materials from the engineering data library. The pre-processing stage generates the tetrahedral mesh, runs the convergence study and applies the cylindrical supports and ball joint forces. The solver stage runs static structural, modal and fatigue analyses. The post-processing stage extracts von Mises stress, total deformation, safety factor, natural frequencies and life. A design check compares these values with the targets, and when a target is not met, or when large low-stress regions remain, the loop returns to the CAD stage for shape refinement before the final design is reported.

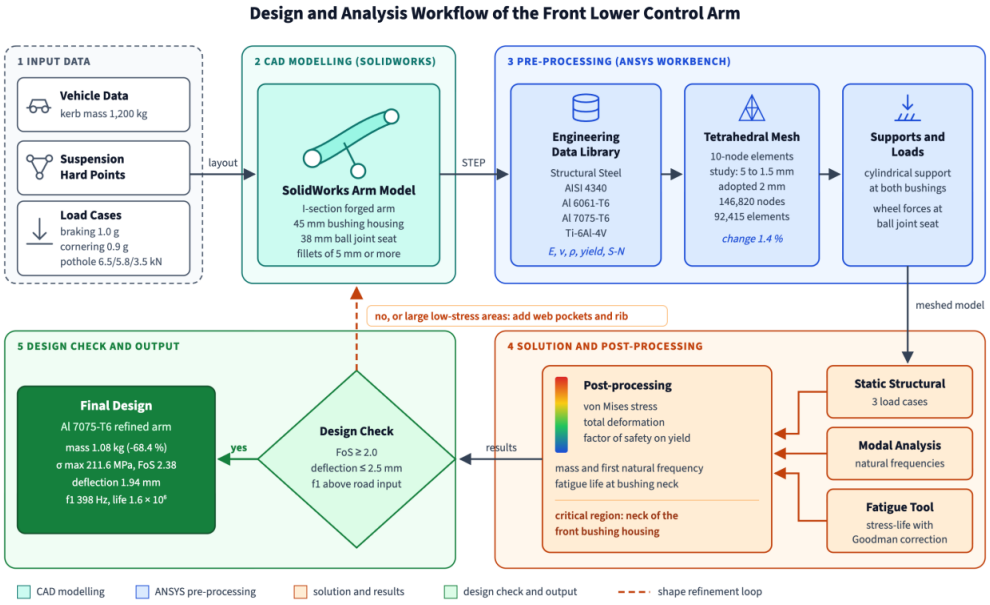


Fig. 1 System Architecture

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V. RESULT AND OUTPUT



Fig. 2 Result and Output Screen

VI. CONCLUSION

A front lower control arm for a MacPherson strut suspension was designed in SolidWorks and analysed in ANSYS Workbench under braking, cornering and combined pothole loads. The combined pothole case governed the design, and the maximum stress in every material appeared at the neck between the arm body and the front bushing housing, which agrees with the failure locations reported for control arms in service. The mesh convergence study confirmed that the peak stress values used for design decisions were not sensitive to further mesh refinement.

The comparison of five materials showed that the stress level was almost the same for all of them, between 181.7 and 189.1 MPa, while deformation, mass and safety factor differed widely. Structural steel gave a factor of safety of only 1.34 at a mass of 3.42 kg, and aluminium 6061-T6 gave 1.52, so neither met the target of 2.0. Forged AISI 4340 and Ti-6Al-4V gave high safety factors of 3.75 and 4.77, but at masses of 3.42 kg and 1.93 kg respectively. Aluminium 7075-T6 met the target with a factor of safety of 2.75 at only 1.22 kg and was selected as the most suitable material.

The refined 7075-T6 arm with web pockets and an inner edge rib reached a mass of 1.08 kg, a mass reduction of 68.4 percent against the steel baseline, with a maximum stress of 211.6 MPa, a factor of safety of 2.38 and a ball joint deflection of 1.94 mm, all within the targets. Its first natural frequency of 398 Hz is far above the road and wheel-hop range, and the predicted fatigue life of 1.6 million cycles at the critical neck is adequate for the intended service. The reduction in unsprung mass is expected to improve ride and road holding.

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Future work can include extraction of load histories from a multibody model of the full suspension, formal topology optimisation followed by forging feasibility checks, nonlinear analysis of the rubber bushings, and physical validation of the predicted stresses with strain gauges on a prototype arm. A cost study comparing forged aluminium with forged steel would also help to decide whether the weight saving justifies the higher material price for a given vehicle segment.

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