High Cyclic Fatigue Behaviour of Varied Pitch Compression Springs for Automotive Applications

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Abstract

In this paper, fatigue life of coil springs was investigated as failure due to high cyclic loading during their service life is more common. For this purpose, two exclusive rear coil compression spring geometries were investigated using material type - silicon-chromium steel SAE-AISI 9254 for this application. For these design models, the effect of changing component geometry using varying pitch arrangements of coils were examined to understand their structural durability and ability to withstand cyclic loading conditions. A finite element model based on industry standard designs were created to simulate real-life spring performance. In this study, the varied pitch designs were subjected to lower stresses in static analysis and have longer life estimates in the fatigue analysis. This confirms that a varied pitch can improve the performance of a coil spring. The result shows that design-1 incorporated a pitch design that reduced pitch at the centre coils of the spring performed better.

Key words: Fatigue analysis; rear coil compression springs; SAE-AISI 9254; Automobiles

1 INTRODUCTION

A spring is an elastic body that a force can twist, pull, or stretch [1] and it stores elastic potential energy equalling the work done to deform the spring. Its primary function is to deform under load and return to its original shape when the load is removed. The coil spring is an essential part of suspension systems in vehicles, supporting the weight of the vehicle and absorbing road irregularities to smooth out shocks [2] and maintain ride comfort for passengers. The load that the spring can carry depends on the overall diameter of the spring, the spacing between coils, the shape of the spring and the diameter of the wire [1]. Most commonly, coil springs fail due to high cyclic fatigue caused by dynamic service loading conditions [3] of everyday use particularly in bad road conditions. Springs are elastic bodies that undergo significant deformation when subjected to a load and they store recoverable mechanical energy in the form of elastic potential energy. The energy stored in the spring is equal to the work done to deform the spring. When the load is removed, the energy stored returns the spring to its original shape and position. Hence, springs are used in designs with the purpose to store energy, to absorb energy, to offer flexibility or to apply a force [2]. The forces produced by springs can be compressive or tensile, and linear or radial [4]. The main functions of springs are a) indicate/control a load (will deflect when subjected to a load) b) apply a definite force – to sustain an exact force irrespective to changes in the environment or provide an operating force or return load in the same way as in a car braking system c) reduce impact and absorb energy by deflecting to retain the energy in a flowing system to avoid any peaks by reducing the size of the force caused by impact/shock loading d) control vibration – isolate vibration by absorbing energy to stop it spreading or isolate a sensitive part from ambient vibration and supporting moving masses by reducing the effect of energy from impact on a system.

An incorrectly shaped spring can lead to instability under compression which causes the spring to tremble and buckle, this means the spring will not be supporting the load correctly and this damages the spring [5]. The end types of these springs affect their response to loading so it is important to select the correct end type for better performance [6] . The four main coiled spring end types are shown in Figure 1. A squared and ground end is prefered for light weight vehicle applications . In this case the last coil is bent, so it is perpendicular to the load but then it is ground to create a greater flat loading surface. Improving the squareness of the end of the spring helps to reduce the chances of buckling under a compressive load [7] . Sometimes the decreased thickness from grinding can be countered by making a double end coil so the second coil acts as reinforcement to avoid weakening the spring. The geometrical parameters have a significant effect on the performance of the springs [6]. Pitch being an important geometrical parameter also affects the behaviour of the springs and therefore there is a need to study the effect of pitch on the spring behaviour in detail [8].

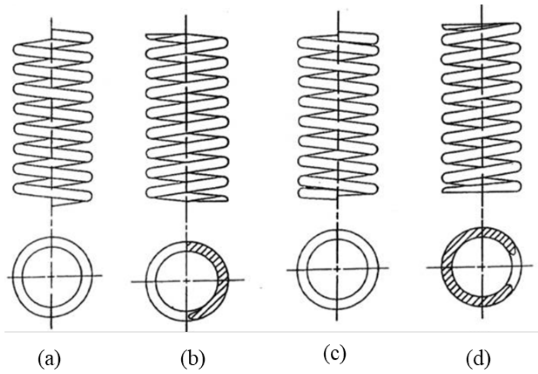

Figure 1: End Types of Compression Springs; (a) Plain Ends, (b) Plain Ends Ground (c) Squared Ends (d) Squared and Ground Ends [8] .

The three loading types that springs may be subjected are static, cyclic and impact. A static load can be compressional or tensional. Cyclic loading is where springs cycle between the loads, they can also be either tensional or compressional. Typically, the spring is loaded in a range that will not exceed the maximum stress of the material and will change/cycle through different loads during operation. A compression spring in suspension needs to be able to withstand the repeated application of stress which causes it to compress and recover repetitively over its lifespan [2]. Finally, impact loading occurs in dynamic environments most commonly when cyclic loading is present [9]. It is a load or tension with great magnitude applied to the spring causing a surge wave through the spring which induces stresses exceeding the regular operating range. If large enough, impact loads can cause sudden failure in springs [10], [11].

Fatigue failure is the most common cause of failure for springs in suspension systems . The cyclic nature of the loading causes microscopic imperfections which grow into cracks resulting in material failure [3]. Springs can usually withstand tens of thousands of cycles before fatigue failure occurs, though the failure can occur sooner, if the loading causes higher stresses close to the elastic limit. The inner surface of an active coil of the spring is a high stress concentration zone [4]. Active coils are any part of a spring that stores and releases energy. In order to improve the maximum fatigue limit, some critical geometrical aspects can be altered within the design. The parameters such as outer diameter of the coil, the number of active coils and the diameter/thickness of the wire all influence the fatigue life of a spring. In addition to this, other defects such as surface imperfections, improper heat treatment and other manufacturing defects can cause fatigue and lead to failure. Another important factor which can reduce the strength of the metal and leaves imperfections is the corrosion [12], [13]. The corrosion sites can be active sites of crack initiation. In the light of discussion, it can be concluded that a variety of factors cause fatigue failure, however it is the combined effect of these factors which causes the failure, which renders the analysis more complex.

Pawar et al. presented an analysis of two coil springs, an existing design and a new design with a reduced number of coils with increased pitch. The new design possessed an outer diameter (OD) of 88mm, wire diameter (WD) of 12mm and 315mm free length (FL). As reported by the authors, the analysis revealed that the new design exhibited an increased stiffness which resulted in an improvement in the load carrying capacity of the spring. Further, the new design was 9% lighter due to a reduced number of coils with increased pitch and was capable of carrying 11% greater load which proved the suitability of the new design [5]. In a related study, Karthikeyan et al. performed a simulation using an alloy of steel and copper. The authors used a working load of 800N, observing a 60% weight reduction [7]. The new design with an OD 66mm, WD 10mm and FL of 210mm was capable of working at the same conditions which makes it a suitable lightweight alternative. The authors further concluded that if the inner side of the coil spring is shot peened, the subjected stresses on the inner surface are reduced which results in improved fatigue life. In another study, fatigue analysis was performed on a spring made from a chromium steel alloy, SAE 9254. The simulation as performed by the authors was adjusted according to the design limits to find the number of cycles required to fail the spring with FL 392mm. The results of the fatigue analysis showed that the design fails after 0.516×10^8 cycles, well above the design requirement of $4\text{x}10^5$ cycles. Therefore, the design as proposed by the authors was declared safe for use [7].

Another important aspect in the design of springs is the material used [14]. A material with high tensile strength and a high yield point (elastic limit) is preferred. Furthermore, a low modulus of elasticity is favourable as it allows for a greater amount of energy to be stored [15]. In view of the industry focus to develop lightweight and efficient cars, designing lightweight springs with improved performance has become important. Composite materials, being a new class of materials can offer a lightweight alternative to steel thanks to their lower density, while maintaining comparable performance. The other favourable properties of composites include better stiffness, wear resistance, corrosion resistance and fatigue resistance [16]. Mahadevan et al. performed an investigation on the alloy helical springs using stress analysis [17]. They used chromium as an additive to metal alloys as it is corrosion resistant and is very hard, while being able to operate under really high temperatures. Other similar alloys such as chrome vanadium and chrome silicon possess good resistance to fatigue with a great endurance for impact loads [18]. In another study, stainless steel, phosphor bronze, chrome vanadium and Inconel 600 were investigated for a helical spring for a two-wheeled vehicle [19]. Each spring was simulated using identical geometry of WD 7.2mm, OD 49.4mm and FL 225mm and the authors reported that the minimum stress and minimum deformation was found in the chrome vanadium, concluding that chrome vanadium was the optimum material for their application. A suitable silicon-chromium steel called SAE 9254 was also proposed by

Kamal and Rahman, as outlined in the above discussion, which was found to exceed the design expectation use [7]. E-glass/Epoxy and Carbon/Epoxy composites were used for springs which resulted in a weight savings of more than 80% compared to the steel spring [20]. They used a spring with WD 12mm and FL 340mm. The simulations carried out by, Nirala et al. revealed that the designed spring was safe for all the materials considered, with the Carbon/Epoxy composite being indicated as the best compared to the traditional steel.

In one another recent study, the geometry of helical springs was investigated using some variable parameters such as the pitch, diameter of the spring wire and spring coil, and total height of the spring. The results show that these variable parameters significantly affect the properties of springs such as stiffness and deformation, and that can be controlled by varying these parameters for a particular application [21].

In one another recent study, researchers analysed the two basic spring designs, variable pitch and cylindrical designs using two commonly used materials - alloy steel (vanadium chrome spring steel) and high carbon steel. The results of analysis showed that the spring was designed successfully and fulfilled the motives of two basic spring designs in a single combined spring structure [22].

The coil springs are designed with different geometries such as spring diameter, wire diameter, coil spacing, and shape, all affect the spring load carrying capacity [8] and their resistance to fatigue. In view of the above discussed literature, it was found that there is a scope to further investigate the effect of varying pitch in the spring design on the spring performance. Varied pitch has previously been used in high performance vehicle suspension springs and commercial vehicles as it can offer multiple tiers of deflection. This concept can also be considered for light weight vehicles.

In this study, the two different spring designs were considered with varying pitch arrangements of coils silicon-chromium steel SAE-AISI9254 material to understand their structural durability and ability to withstand cyclic loading conditions. Design-1 incorporated a design where the pitch was smaller at the centre, while design-2 had an increasingly larger pitch towards the centre of the spring. The SAE-AISI9254 steel was selected as it is a suitable material that is used currently for manufacturing coil springs in aerospace and automotive industries. In this study, both compressional static loading and cyclic fatigue loading conditions have been used to elucidate the effect of the varied pitch on the spring performance.

2 Material and Methods

(a) *Material*

The silicon-chromium steel SAE-AISI was investigated for this study. Table 1 shows the detailed material properties [10] [8] [24].

Table 1: Properties of selected material [10] [8] [24].

SAE 9254	
Poisson ratio	0.27
Density (kg/m^3)	7700
Young’s modulus (GPa)	205
Yield Strength (MPa)	2270

(b) Geometry of the models

A base design was used which more closely reflects a spring used currently for various industrial applications and all other designs were analysed with respect to this design. The base design was created using an industry standard rear coil compression spring suitable for light vehicles, specifically a BMW series 1 from autodoc.co.uk [11]. This was done primarily so as to simulate real-life loading conditions and the results obtained are very relevant to the application for use in suspension of light vehicles. The literature revealed very little information related to varying pitches in case of springs. All other spring geometrical parameters were kept constant and only the effects of changing the pitch geometry we considered. Design-1 incorporated a design where the pitch was smaller at the centre. Contrary to this, design-2 had a large pitch towards the centre of the spring. The other parameters were a free length of about 340mm, an outer diameter of 100 mm, a wire diameter of 13 mm and nine number of coils. The only variables in the designs were material and specific geometry. The Helix/Spiral feature in Solidworks is used to create the design of the pitch and outer diameter, the values of the pitch are entered accordingly to replicate the closed and ground ends. The pitch values could also be edited to create the other models where the designs incorporate varying pitch. A small, extruded cut was made at the ends of the squared spring to create the ground effect for the end type. Then a simple extruded boss was added to the ends of the spring in the shape of a short cylinder which allowed for the model to be constrained to only vertical loading and deformation. The helix/spiral feature is edited, and the values changed accordingly to make two further models that are used in the simulations. The pitch data and spring model of all three designs are presented in Table 2 and Figure 2 respectively. Within the pitch data, the revolution of the coil (Rev) is stated, with corresponding values for pitch (P), total height (H) and outer diameter (Dia). The diameter of the wire is 13mm.

Table 2: The pitch data with Helix/Spiral parameters.

Reginal Parameters												
	Base Design				**Design 1**				**Design 2**			
	P (mm)	Rev	H (mm)	Dia (mm)	P (mm)	Rev	H (mm)	Dia	P (mm)	Rev	H (mm)	Dia (mm)
1	15	0	0	100	15	0	0	100	15	0	0	100
2	15	1	15	100	20	1	17.5	100	20	1	17.5	100
3	43	2	44	100	60	2	57.5	100	20	2	37.5	100
4	43	3	87	100	55	3	115	100	40	3	67.5	100
5	43	4	130	100	20	4	152.5	100	50	4	112.5	100
6	43	5	173	100	21	5	173	100	71	5	173	100
7	43	6	216	100	20	6	193.5	100	50	6	233.5	100
8	43	7	259	100	55	7	231	100	40	7	278.5	100
9	43	8	302	100	60	8	288.5	100	20	8	308.5	100
10	15	9	331	100	20	9	328.5	100	20	9	328.5	100
11	15	10	346	100	15	10	346	100	15	10	346	100

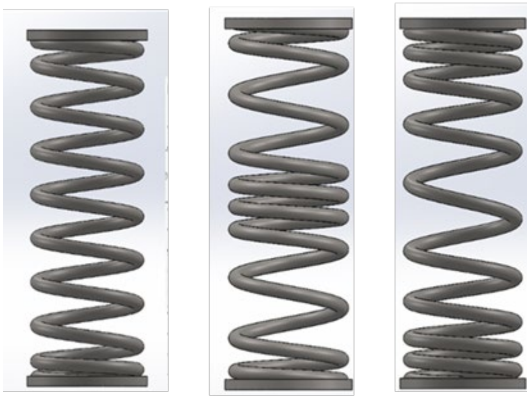

Figure 2: Shows the coils arrangements for all three designs (a) Base Design, (b) Design-1 with smaller pitch at the centre, (c) Design-2 with increasingly larger pitch towards the centre of the spring.

(c) Loads and Boundary Conditions

This study assumes the weight of the light vehicle with five passengers is 1600kg. This was based on a vehicle weight of 1200kg and passenger weight of 80kg, $1200 + (80 \times 5) = 1600$kg. The total load of the vehicle on the wheels was assumed as $1600 \times 9.8 = 15680$N. It is also assumed that there was an even weight distribution as the vehicles considered are not high performance. This means the total load on one wheel was 3920N.

For the fatigue analysis, stress versus the number of cycles (SN-curve) data was required for each material. This shows the stress which the material can endure at a given number of cycles before it would likely fail. For many materials this specific data can be found in the form of a graph of stress vs number of cycles, though with the material (SAE 9254 silicon-chromium spring steel) in this investigation this information is not so forthcoming. The cyclic yield strength can be used to calculate an estimated value of the fatigue limit. This calculated value can then be used in the fatigue analysis. The equation used for estimating the fatigue limit is as under [25]:

$\sigma_{-1} = 1.13{\sigma_s}^{0.9}$

Where σ_{-1}= fatigue limit and σ_s= cyclic yield strength

$= 1.13 \times 1922^{0.9}$

= 1019.7 MPa

(d) 3D modelling and finite element analysis

Models of the coil springs were developed using Solidworks 2020. The models are 3D and made to the same scale of typical industry standard springs. Static loading tests were carried out to provide a stress/strain analysis of the different models. Thereafter, fatigue analysis was performed, this more accurately depicts the typical loading the spring would endure in regular use in suspension systems. The load applied in the simulations was a vertical force on the flat surface of the end coil, the opposite end of the spring was fixed in place to replicate operation in the real world as it cannot move away from the force, it is subjected to resistance from its fixing. The fatigue analysis involves subjecting the models to cyclic loading and helps determine the resistance to fatigue and the potential component life. A number of different designs were developed and created as models in Solidworks so that the effects of the changes can be identified and quantified. This leads to a better understanding of how the spring performs in operation and will allow for recommendations of the optimum design to be made.

Two sets of simulations were performed, a static analysis of the proposed designs for each of the chosen materials, followed by a fatigue analysis. The load was applied normal to the selected face on the top end of the spring, ensuring the force is only in one direction, vertically down. The load replicates the weight of a light vehicle with five passengers. The spring was also fixed in place to provide resistance to the loading, allowing it to behave appropriately by deforming under load. Finally, a mesh needs to be created; meshing creates the elements of the components that will be analysed in the study. A fine mesh is created as Figure 3(a) demonstrates, because this makes the elements analysed smaller as seen in Figure 3(b). In turn, this gives more accurate results (the mesh size is consistent for every study). Once the mesh is created, the simulation can run, and the results can be gathered. These steps are performed for each model to perform analysis all the designs.

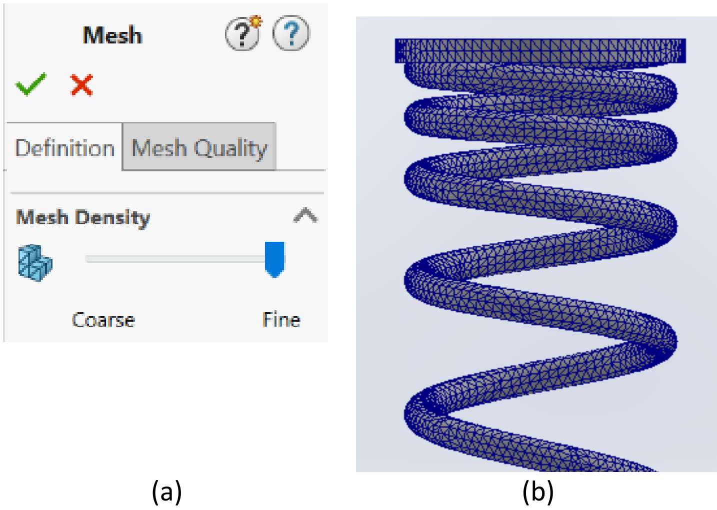

Figure 3: Created mesh on the spring model

The fatigue study uses the data captured from the static study performed before it. It uses the stresses induced on the model from the static analysis to create the loading event. An SN-curve was created which is a plot of the magnitude of an alternating stress versus the number of cycles it takes to reach failure at that stress for the given material. The specific SN-curves for the materials selected were not available so the values used were estimated and presented with the material properties above. The data was generated by assuming the yield strength was the stress limit for low cycle fatigue, estimated to be around 100 cycles. Furthermore, the value of fatigue limit of 1019.7 MPa for SAE 9254 was calculated using the value of cyclic yield strength of 1922 MPa defined from literature by [9] & [7]. The value for fatigue limit was used as the stress limit at 10^7 cycles as this is considered an appropriate point to estimate the fatigue limit of a component.

3 RESULTS

(a) von Mises Stress Distribution

Firstly, the induced von Mises stresses from the static analysis were recorded in each study as this shows how the design geometry causes stress to be distributed and how well the material selection can cope with such stresses. Close reference is paid to the material's yield strength; for the spring to operate successfully in the scenario simulated, it will require the von Mises stresses to be below the yield strength. This means any deformation will be elastic, so the model can return to its original shape when the load is removed. Figure 4 shows von Mises stress distribution for all three models using SAE 9254 material type.

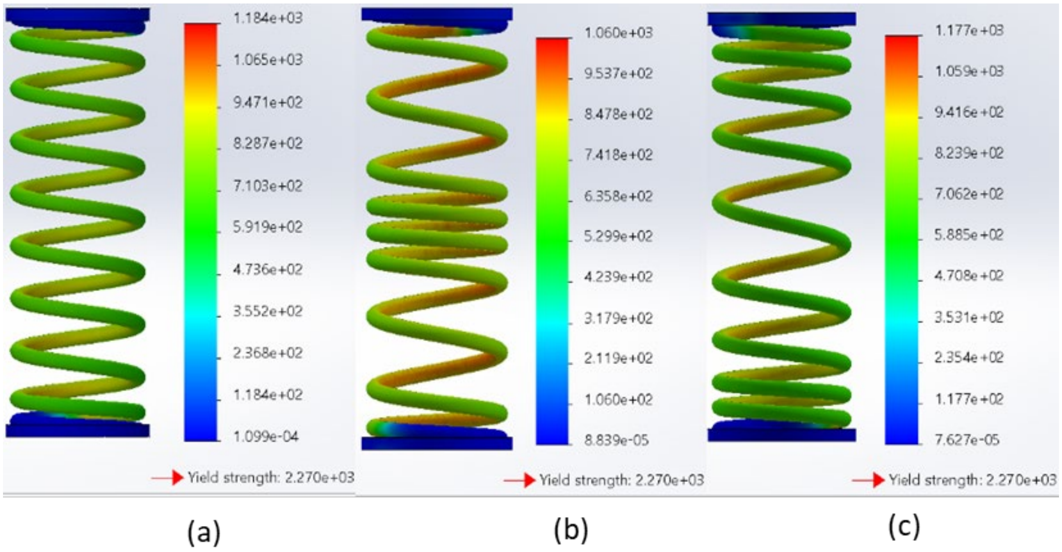

Figure 4: von Mises stress distribution (in MPa) for all three models using SAE 9254 material type (a) Base Design, (b) Design-1 and (c) Design-2.

(b) Static Displacement

Secondly, from the static analysis, the maximum displacement of the model under loading was recorded. The intention of the spring design for suspension is to deform and absorb energy to reduce the impact on the vehicle and subsequently, the passengers on board. The different pitch designs affect the maximum displacement of the model as seen in the results. Maximum displacement is seen at the top end of the spring, this is because the bottom end is fixed in position as part of the simulation. So, when the load is applied, the top end is pushed down and the spring compresses, while the bottom edge remains in the same position. Figure 5 shows von Mises stress distribution for all three models using SAE 9254 material type.

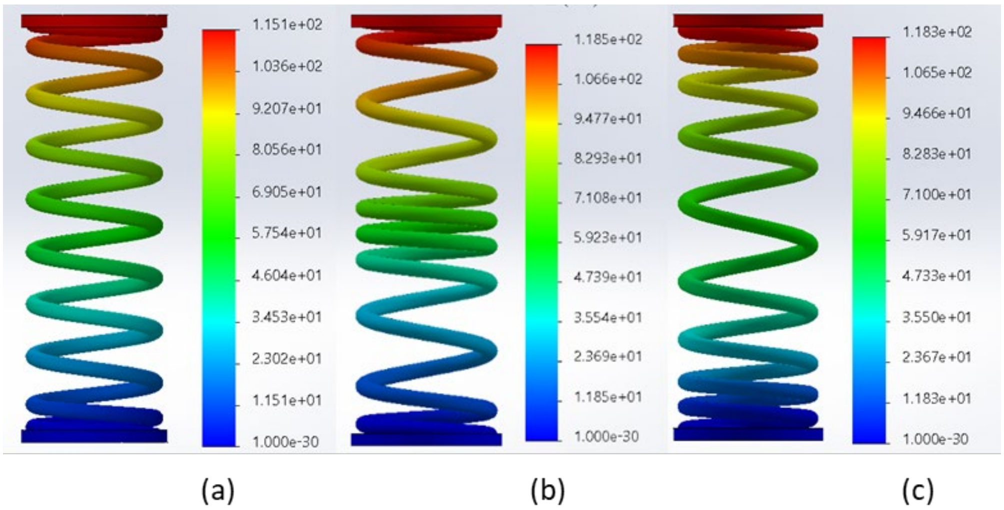

Figure 5: Static Displacement (in mm) for all three models using SAE 9254 material type (a) Base Design, (b) Design-1 and (c) Design-2.

(c) Fatigue Analysis

For this analysis, the fatigue life (in cycles) was given for the model at the different stress locations. For example, the part of the model with the lowest expected fatigue life will be the critical location where the maximum von Mises stress was found. The optimum results for this part will be the longest expected fatigue life at the critical location when compared to the other models. The longer the expected fatigue life, the better the model resists the induced stresses caused from cyclic loading. Figure 6 shows von Mises stress distribution for all three models using SAE 9254 material type.

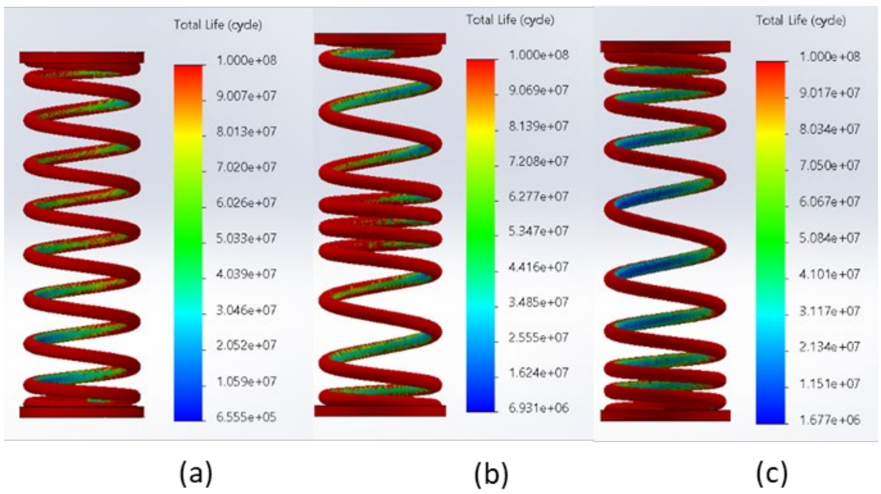

Figure 6: Fatigue life (cycles) for all three models using SAE 9254 material type (a) Base Design, (b) Design-1 and (c) Design-2.

4 Discussion on results

The operational requirements of the designed springs are to reduce impact and absorb energy to ensure a smooth ride without sudden shocks. To do this, springs deflect under loading, as demonstrated in the simulations. Every model deflected, as expected, under load which proves they were absorbing the energy from such loading and consequently reducing the effect of the energy from impact.

The base design was used for this study as it closely resembles an industry standard rear coil spring; the model was very similar to that of one used for a BMW 1 series. The reason for modelling the spring like an industry standard spring was so real-life loading conditions could be used in the simulation, meaning the results are very relevant to the application – use in suspension of light vehicles. To develop the investigation, two further designs were created. Following a thorough review of relevant literature, little information relating to varying pitches was found, which formed an opportunity to investigate this in more detail. All other spring geometry remained unchanged, as only the effects of changing the pitch geometry were to be considered. Design 1 incorporated a design where the pitch was smaller at the centre, while oppositely, design 2 had an increasingly larger pitch towards the centre of the spring.

The results from the static analysis regarding the maximum von Mises stresses for each model are summarised in Figure 7. It is favourable for the model to experience lower stresses because this means it is less likely to fail from repeated loads due to fatigue. The shows that the maximum von Mises stress induced in SAE 9254 base design of spring is 1184 MPa, which is of the same order of magnitude as the maximum von Mises stresses found on the model used in the previous study [8], shows that the accuracy is appropriate. The result also shows that the design-1 (reducing the pitch at the centre coils) had the lowest induced stresses compared to the other two models. On the contrary, the largest value of stress was found on the base design at 1184 MPa.

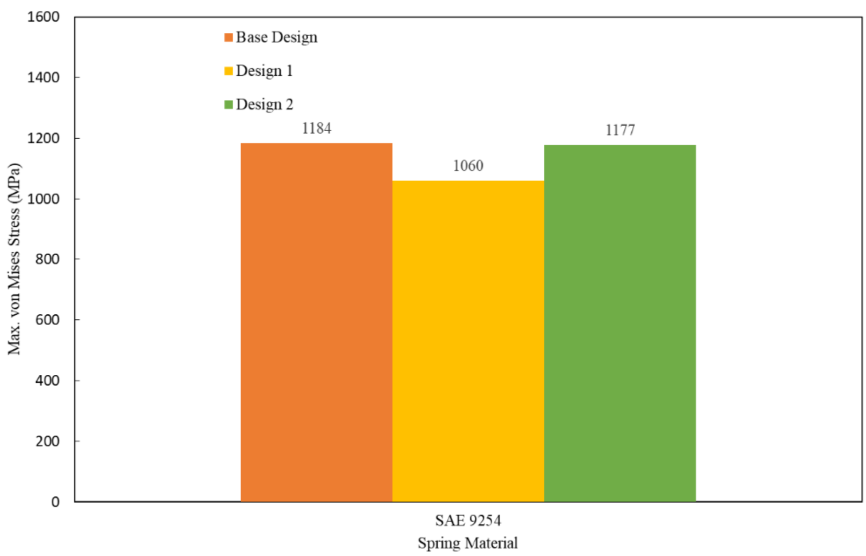

Figure 7: Maximum von Mises Stress found in each model.

The other set of results obtained from the static analysis was concerning the maximum displacement of the model, shown below in Figure 8. The graph visibly demonstrates how the difference between displacement values for the same material were minimal. Furthermore, the operational requirements of the designed springs are to reduce impact and absorb energy to ensure a smooth ride without sudden shocks. To do this, springs deflect under loading, as demonstrated in the simulations. Every model deflected, as expected, under load which proves they were absorbing the energy from such loading and consequently reducing the effect of the energy from impact.

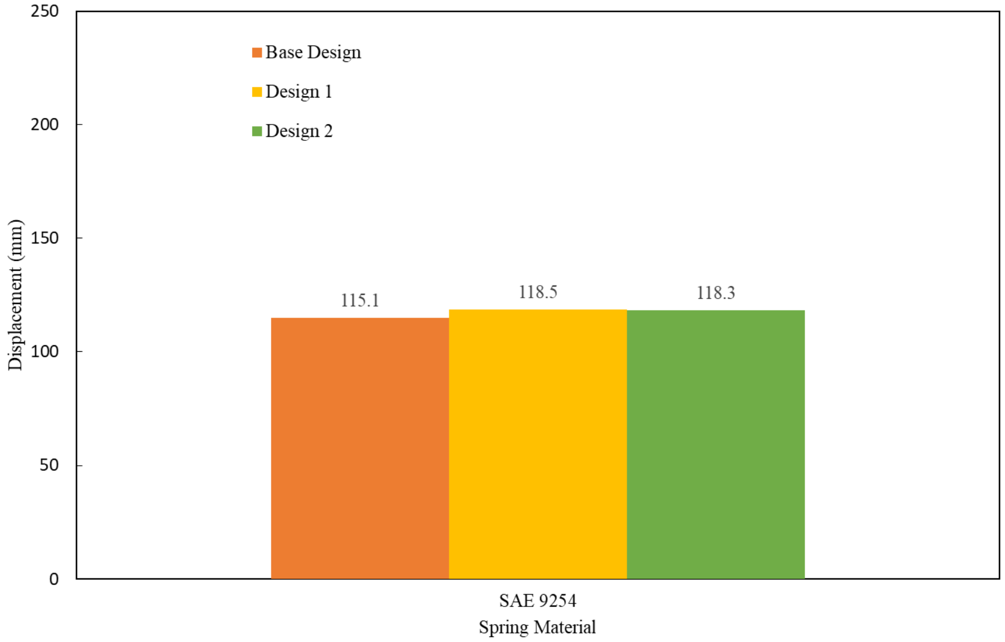

Figure 8: Maximum displacement found in each model.

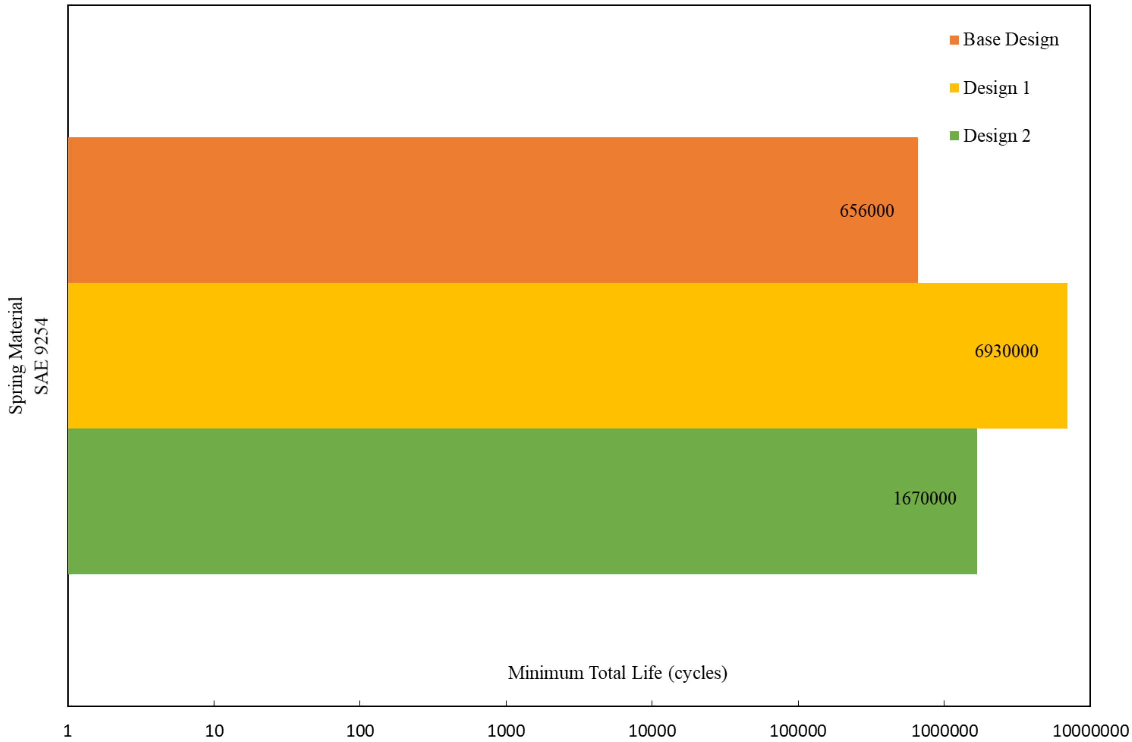

Figure 9: Minimum Total Life (cycles) found in each model.

The fatigue study produced data points on each model stating the total available life of the component under cyclic loading. Each data point was different due to the induced von Mises stresses on the model varying as seen in the simulation screen captures above. To find the minimum expected life of the component, the total life is found at the critical location. This is where the stress is most concentrated on the model and would likely be the location of the first cause of fatigue failure. Figure 9 shows the total life in cycles of each model. The values for total life are displayed on a logarithmic scale as this is the most effective way to visualise the different values. The shortest life was found for the base design and the longest life was for design-1. The longest life was for design-1 on the SAE 9254, found to be 6930,000 cycles – 11 times greater than the total life of base design for the SAE 9254 material. The critical location is shown in Figure 10 as the darkest blue regions are where the stress is most concentrated, found on the inner face of the spring. This means that cracks would start to form at these locations; such cracks then grow as loading continues until the whole component fails.

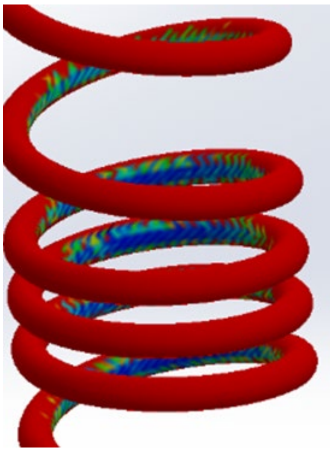

Figure 10: Critical location on Design-1

The simulation offers evidence that design-1 (reduced pitch at the centre coils of spring) would be able to operate much longer than the other designs if subjected to the same loading. Thus, this must be taken as a recommendation as an optimal design in which the performance of the rear coil compression spring is enhanced.

In this study, the SN-curve data was difficult to source for the better performing spring materials which caused difficulty as the simulations could not progress without this relevant data. Calculations and estimates were used to produce the best model possible so this study could go ahead. More extensive data would improve the accuracy and reliability of the studies; however, this just was not available for the optimum materials. The accessibility of detailed material information was restricted, they may have been accessible at a cost in some leading journals and/or datasheets, though these were not available to support these studies.

This study provides evidence of successful simulations that provide relevant and effective ways to optimise performance of suspension springs used in light vehicles. It offers a new pitch design that could have potential use within the automotive industry. There is scope to further investigate potential materials to apply to the proposed model to optimise performance, one of which being chrome vanadium. Literature highlights its high-performance capabilities, though there was not sufficient data to complete simulations with this material. With better accessibility to such information, simulations using chrome vanadium can be produced. Also, as mentioned, SN-curve data was scarce for the optimal materials, so in the future it would be beneficial to access this, as well as more effective ways to generate SN curves as this would improve accuracy and reliability of the simulations.

The loading conditions were set up to create a force normal to the free length of the spring, further studies could be conducted to see how the models behave when the load is on an angle as the springs are not designed for this type of loading but could be subjected to it in use. Further optimisation of the design would be useful, including real-life modelling and testing of the component.

5 Conclusion

The most common cause of failure in coil springs is due to fatigue failure; cracks forming due to repeated loading, which grow over time and result in critical damage. For this purpose, two unique rear coil compression spring geometries were investigated using the material type of silicon-chromium steel SAE-AISI for this application.

The focus of this study was on changing the pitch within the spring designs. A constant pitch base design was used along with two designs with varied pitches. The varied pitch designs were subjected to lower stresses in static analysis, particularly for design-1 that was incorporated a reduced pitch at the centre coils of the spring and showed 10 to 12 % less stresses. This study confirms that a varied pitch can improve the performance of a coil spring. The simulations conclusively prove that design-1 performed the best and produced the lowest von Mises stresses out of all the simulations, suggesting the geometry makes the spring more resistant to the load and safer. Though, when the fatigue study is considered, it reveals that the longest fatigue life for the design-1 is 11 times greater than base design for SAE 9254.

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