Design and Analysis of Crossplane 4200 cc V8 Engine

Muhammad Abdullah Zafar Ghauri[a*], Abdullah Zafarullah[a], Muhammad Azhaf Zeeshan[a]
Zainab Hameed[a]

[a]School of Mechanical and Manufacturing Engineering (SMME), National University of Sciences and Technology (NUST), H-12, Islamabad Capital Territory (ICT), 44000, Pakistan

mghauri.ug22smme@student.nust.edu.pk

azafarullah.ug22smme@student.nust.edu.pk

mzeeshan.ug22smme@student.nust.edu.pk

zhameed.ug22smme@student.nust.edu.pk

[*]Corresponding author: Muhammad Abdullah, MAZG, Zafar; `mghauri.ug22smme@student.nust.edu.pk`

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Abstract

This report aims at evaluating a V8 Crossplane Crank Assembly (4200 cc) based on Maserati F136 R engine and modeling individual parts using SOLIDWORKS 2021 to create finished assembly and using SOLIDWORKS 2024 Static Structural interface for analyzing stress concentration on piston cylinders using necessary calculations.

Keywords: V8 engine; Crossplane; SOLIDWORKS 2024; Static Structural; stress analysis

1 Introduction

1.1 History

As the name implies, a V8 engine comprises of eight cylindrical engines, where two banks of four cylinders share the same crankshaft, while the engines are arranged in "V" configuration. Nunney (2006) As automotive technology advanced, the first V8 engine was designed and built in 1904, referred to as "Antoinette" by French company "Antoinette" for use in cars, speedboat racing, cars and later in airplanes. Small scale production for V8 engines began in 1904 as well by Renault and Buchet for use in race cars. Wagner (2020) Pearce (2016) UniqueCarsandParts (2023)

1.2 Design and Types

While most of cars manufactured nowadays use engines with "V" configuration, however "W" engines also exist in the market. As most engines use "V" angle (the angle between two banks of cylinder) of 90° , an ideal angle for providing good engine balance resulting in low vibrations Huffman and Quiroga (2011). However, referring to design configuration, the downside has relatively greater width as compared to those using smaller V-angle. Both the Ford and Volvo engines were used in transverse engine chassis, which were designed for a front-wheel-drive layout (with an on-demand all-wheel drive system in the case of the Volvos). Mitigating the effects of vibrations to some extent, Volvo engines used balance shaft and offset split crankpins McIntosh (2013). The Rolls-Royce Meteorite tank engine also used a 60-degree V-angle, since it was derived from the 60 degree V12 Rolls-Royce Meteor which in turn was based on the Rolls-Royce Merlin V12 engineRobson (1977). However, several other V-angles have been used in the past, for example Lancia-Trikappa, Lancia Dilambda and Lancia Astura produced between 1922 and 1939, used wide V-angle primarily ranging between 14°-24° Daniels (2000). Miller fou-wheel drive racing cars produced in 1932 used V8 engine with an angle of 45° Borgeson (2000). A typical V8 engine's displacement varies typically from 3.5 to 6.4 L. however, some large and small examples have been produced over time such as 8.2 L Cadillac Eldorado produced between 1971 and 1978 and BMW 3.0 L M60B30 V8 engines, which are intended for motor-sport and often they are short-stroke and small in size to maximize torque and hence power, for which Cosworth DFV 3.0 L is a good example. Since V8 engines are large in size, they are used on cars with longitudinal engine layout and rear-wheel drive (or all-wheel drive). Transverse engine and front-wheel drive vehicles have also used V8 engines, the purpose being fulfilled by using closer cylinder bore spacings and narrower cylinder bank angles to reduce their space requirements.TheAutoChannel (2008)

Following are the types of V8 crankshaft configurations:

1. Crossplane V8 Crankshaft
2. Flat-plate V8 Crankshaft

1.2.1 Flatplate V8 Crankshaft

The flatplane crankshaft is often used in internal combustion engines having an angle of 180° between crank throws. Torchinsky (2014) Cadillac first introduced them in 1923. Gillogly (2014)Markus (2021) Historically, flatplane V8 engines have been used in large vehicles such as Sherman Tank equipped with Ford GAA engine which comprised of 32-valve DOHC 60° liquid cooled V8. However, flatplane engines are no longer in use commercially as they are prone to excessive vibrations and they are relatively loud. On the other hand, flatplane V8 engines have simpler construction geometry and they are inherently lighter with greater revving limit, hence they are optimum choice for sports and racing cars. On broader perspective, flatplane crankshafts are assosiated with European car manufacturers such as Ferrari and Lotus, while crossplane crankshafts are assosiated with American car manufactureres such as Lancia and Ford. The 2023 model year Chevrolet Corvette Z06 has the largest flat-plane V8 ever seen in production cars at 5.5 litres.Perkins (2021)
Flatplane V8 engine works similar to two-in-line 4 cylinder engine mated together with firing order of Right-Left-Right-Left-Right-Left-Right-Left pattern.Torchinsky (2014) Such configuration allows the engine to rev much faster, making them suitable for racing engines.Clark (2019)

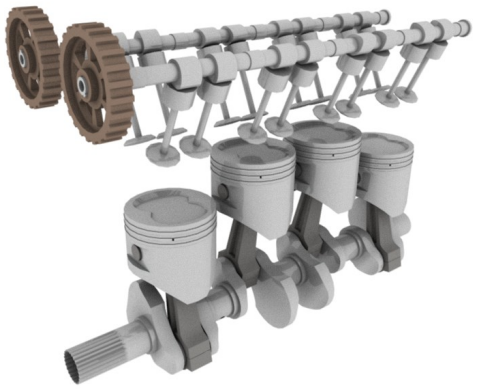


Figure 1: CAD model of DOHC inline-four engine, including the flat-plane crankshaft

1.2.2 Crossplane V8 Crankshaft

A crossplane or cross-plane is a common crankshaft design for piston engine with angle orientation of 90° between the two crank throws, where the angle is phase in crank rotation. It is the most popular crankshaft configuration used in V8 road cars since it produces less vibrations due to perfect primary and secondary balance. The most common crossplane crankshaft for a 90° V8 engine comprises of four crankpins, each serving for the two cylinders on opposing banks, offset at 90° from the adjacent crankpins. The first and last of the four crank pins are at 180° with respect to each other as are the second and third, with each pair at 90° to the other, so that viewed from the end the crankshaft forms a cross. The crankpins, are in two planes being crossed at 90^0, which provides the name *crossplane.* A typical crossplane crankshaft may have nine main bearings for eight throw design and usually five bearings supporting the four throws each with shared crank pin. First proposed in 1915 by Cadillac and Peerless, crossplane design succeeded the flatplane V8 configuration, with Cadillac introducing one in 1923 and Peerless in 1924 on their cars, thereby being on strict competition with each other. One of primary reasons for crossplane design was to produce a much smoother engine than one possible with flatbed configuration. Since, the four engines reciprocate and stop simultaneously in both banks, the second-order forces inherent to the flatplane design stack up and become noticeable in large displacement engines. Each bank of the such engine has four distinct piston phases that cancel the second-order free forces entirely, leaving only minor vibrations due to variation in masses of components during manufacture. Crossplane V8 engines are very heavy due to heavy counterweights, which implies they are not free reeving as flatplane engines. Considering Chrysler Hemi V8 had heavy counterweights, yet the middle two positions on both sides of the center main bearing (the third of 5 mains) did not have any counterweight. Since, these positions are located close to the center of engine, they contribute less to countering any rocking motions - hence the use of external balance weights (e.g. in the crank nose pulley), which requires less extra mass for the same balancing effect. Due to uneven fuel firing about each bank, as well as the 90° piston phases, lead to noticeable torsion for which they have tuned mass dampers which are usually

on the free end of the crankshaft.
V8 engines produce a distinctive rumbling sound due to uneven firing order within each of two banks of four cylinders each. A usual firing order of L-R-L-L-R-L-R-R (or R-L-R-R-L-R-L-L) results in uneven intake and exhaust pulse spacing for each bank. When separate exhaust systems are used for each bank of cylinders, this uneven pulsing results in the rumbling sound typically associated with V8 engines. However, racing engines seek to avoid these uneven exhaust pressure pulses to maximize the power output.

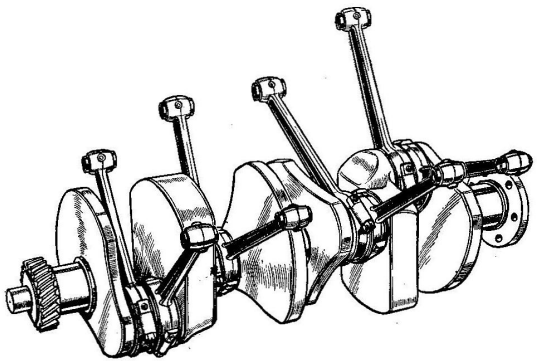


Figure 2: Ford V8 Crossplane Crankshaft Assembly

2 Designing of Crossplane V8 Engine

The main aspect of this project is the designing and assembling a V8 engine with crossplane crankshaft. SOLIDWORKS 2021 and 2024 shall be used for designing and rendering. Since the entire assembly of an engine is a complex and tedious procedure, here this project is aimed at understanding the basic working mechanism of crankshaft and how the movement of pistons by fuel firing drives it to produce torque to move the rotatory parts within the engine. The analysis is aimed at following parts of assembly:

1. Connecting rod
2. Piston Head
3. Crankshaft

2.1 Connecting Rod

A connecting rod is one of primary parts in any engine (primarily internal combustion engine) which cpnnects the piston to the crankshaft. It, along with the crank itself, convert the reciprocating motion of piston to the rotation of crankshaft¿ It trasnmits the compressive and tensile forces from the pston, while in an internal combustion engine, allows for pivoting on piston end and rotation on shaft end.

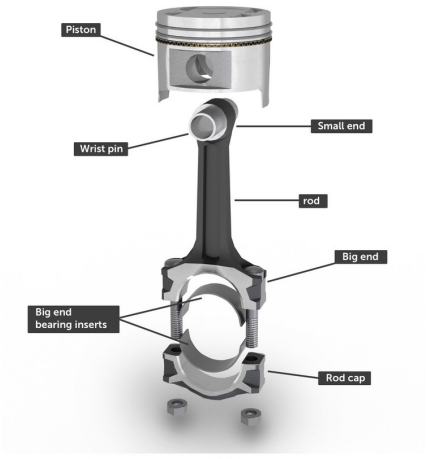


Figure 3: Labeled figure of connection rod with piston head mounted

Connecting rods with rolling element bearings are typically a one piece design where the crankshaft must be pressed together through them, rather than a two piece design that can be bolted around the journal of a one piece crankshaft. It has the tendency to rotate at both ends, thus allowing the angle between the connecting rod and the piston to change as the rod moves up and down and rotates around the crankshaft.
Referring to this project, the connecting rod sans piston head has been devised in SOLIDWORKS 2021 as a single file. The CAD model is shown as follows:

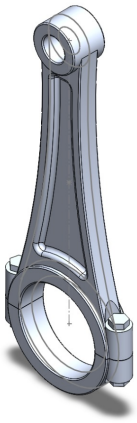


Figure 4: Connecting rod

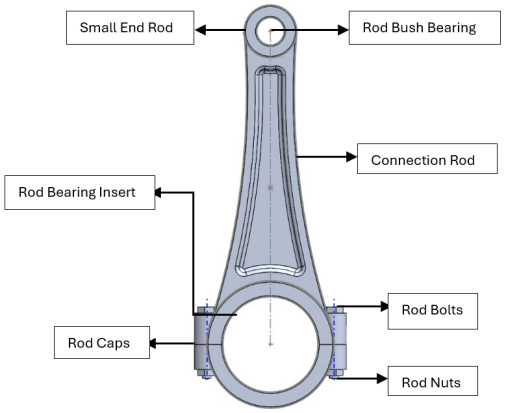


Figure 5: Labeled connecting rod

Following are some important components in connecting rod;

1. Small end rod
2. Big end rod
3. Rod bearing insert
4. Rod nut and bolt
5. Rod cap

2.1.1 Small End Rod

About the small end rod, the connecting rod is connected to fact of piston pin.

2.1.2 Big End Rod

The end at which the connection rod is attached to the side of crank pin is referred to as big end rod.

2.1.3 Rod Bearing Insert

The ends of connection rod are fixed by means of bush rod bearing. Usually a bush is fitted with solid eye is attached to small end of connecting rod while the bigger end is attached to crankpin.

2.1.4 Rod Cap

Shell bearings have an adjustment for wear, but it controls the running and the side clearance allows the bearing cap to be tightened correctly.

2.1.5 Rod Bolt and Nut

After fitting the connecting rod to bottom of crank, the sides are fastened by means of bolts and nuts, which hold the assembly tight in place.

2.2 Piston Assembly

Piston is the primary and important component of reciprocating engine as far as internal combustion engines are concerned, contained in a cylinder and made gas-tight by means of gas rings which tend to maintain pressure within the cylinder. Piston tends to transfer force arising from expanding gas in cylinder to the crankshaft through connecting rod. Pistons are manufactured by casting of aluminum alloys, however for better strength and fatigue lift they are also forged¿ Pistons are designed to certain extent of ovality and profile taper which is so minute that it is insignificant to naked eye, meaning that they are not perfectly round and their diameter is larger near the bottom of skirt than at the crown. As discussed above, an efficient and effective piston is one with maximum gas sealing, which is achieved by use of number of Gas sealing is achieved by the use of piston rings. These are a number of narrow iron rings, fitted loosely into grooves in the piston, just below the crown. The rings are split at a point in the rim, allowing them to press against the cylinder with a light spring pressure. Two types of ring are used: the upper rings have solid faces and provide gas sealing; lower rings have narrow edges and a U-shaped profile, to act as oil scrapers. There are many proprietary and detail design features associated with piston rings.

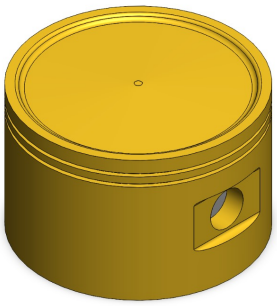


Figure 6: Piston head assembly

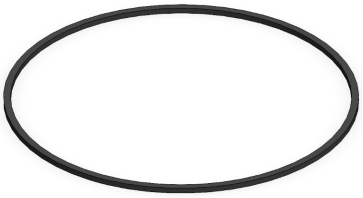


Figure 7: Piston Ring

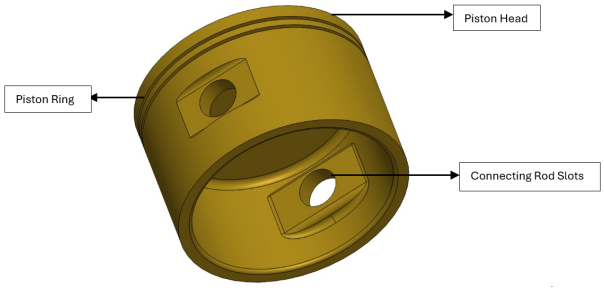


Figure 8: Labeled piston head assembly

Following are three main important parts of piston head assembly:

1. Piston Head
2. Piston Ring
3. Connection Rod Pin

2.2.1 Piston Head

The piston head is the top surface (closest to the cylinder head) of the piston which is subjected to tremendous forces and heat during normal engine operation.

2.2.2 Piston Ring

A piston ring is an expandable split ring used to provide a seal between the piston an the cylinder wall. Piston rings are commonly made from cast iron. Cast iron retains the integrity of its original shape under heat, load, and other dynamic forces. Piston rings seal the combustion chamber, conduct heat from the piston to the cylinder wall, and return oil to the crankcase. Piston ring size and configuration vary depending on engine design and cylinder material.

2.2.3 Connection Rod Pin

Piston pin, or commonly referred to as connection rod pin is a small hollow shaft which connects the connecting rod to the piston.

2.3 Crossplane Crankshaft Assembly

A crossplane or cross-plane is a common crankshaft design for piston engine with angle orientation of 90^{o} between the two crank throws, where the angle is phase in crank rotation. It is the most popular crankshaft configuration used in V8 road cars since it produces less vibrations due to perfect primary and secondary balance. The most common crossplane crankshaft for a 90° V8 engine comprises of four crankpins, each serving for the two cylinders on opposing banks, offset at 90° from the adjacent crankpins. The first and last of the four crank pins are at 180° with respect to each other as are the second and third, with each pair at 90° to the other, so that viewed from the end the crankshaft forms a cross. The crankpins, are in two planes being crossed at 90^{0}, which provides the name *crossplane.*
Referring to modeling of crossplane assembly in SOLIDWORKS, following model has been created effectively. The crankshaft comprises of single crankpin and translationally arraying it four times, here since eight cylinders have been used so two con rods attached at single pin. This crankshaft has been oriented at 90^{o}. Figure 9 shows the assembly with Figure 10 depicting the labeled crankshaft and the interconnecting parts involved.

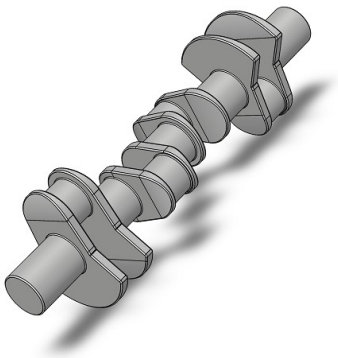


Figure 9: Crossplane crankshaft assembly

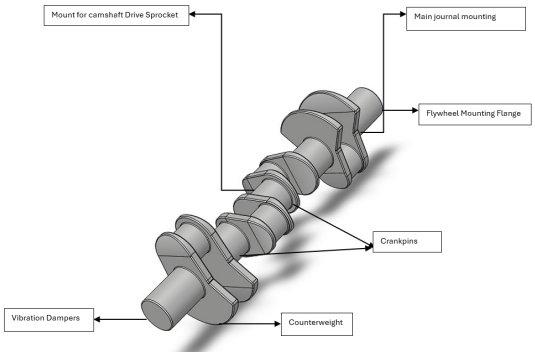


Figure 10: Labeled crankshaft assembly

Following are some important features of a crankshaft assembly:

1. Counterweights
2. Vibrational Dampers
3. Crank Pins
4. Flywheel Mounting Flange
5. Main Journal Mounting
6. Mount for Camshaft Drive Sprocket

2.3.1 Flywheel Mounting Flange

About flywheel mounting flange, as the name suggests, the flywheel is mounted on crankshaft. Typically, a "dowel" for easy location for bolts and nuts to adjust and fit is mounted on it, which helps in locating holes through which there is no misalignment of the bolts.

2.3.2 Crankpins

Through crankpins, lubricating oil flows towards the end of connecting rod. The flow of lubricant only takes place provided there is some matching between holes of crankpin and bearing.

2.3.3 Counterweight

Counterweights are added while they aim at reducing the vibrations which occur due to movement of pistons within the cylinder. They are also aimed at providing rigidity to the crankshaft.

2.3.4 Main Journals

Connecting rods fit about main journal, for some V engines there are two or more connecting rods, however for inline engines, only one connecting rod fits the main journal.A four cylinder inline engine will have five main journals.

2.3.5 Vibration Dampers

About the ends of crankshafts, there are certain spaces upon which vibration dampers are mounted, and as the name implies, they are added to reduce the magnitude of vibrations thereby protecting the engine and its components from damage.

2.3.6 Camshaft Drive Sprocket

Drive sprockets are extensively used for transmission of power from crankshaft to the camshaft.

3 V8 Crossplane Crankshaft Assembly and Rendering

3.1 Calculation of Engine Displacement

The V8 Crossplane Crankshaft assembly was devised from individual parts, respectively as piston assembly, crankshaft and connection rods. Crossplane V8 engine based in Maserati F136 R was used for reference having the capability of 4200 cc approximately. Since the engine's main dimensions could not be sought online as no information was available, hence only the bore diameter and stroke length was sourced online. All the work apart from the two quantities was based on mere assumptions to produce an engine with accuracy of 1 mm. The engine capacity can be calculated from following formula:

$$cc = \frac{\pi * (Bore)^2 * (Stroke) * (N)}{4}$$

Where "cc" stands for engine displacement, "bore" refers to the bore dimater, "stroke" refers to the stroke length and "N" refers to the number of cylinders. For designing of following engine based of Maserati F136 R V8 crossplane engine, following parameters were taken into account:
Bore Diameter = Bore = 92 mm = 0.092 m
Stroke Length = Stroke = 79.6 mm = 0.0796 m
Number of cylinders = N = 8

$$cc = \frac{\pi * (0.092)^2 * (0.0796) * 8}{4}$$
$$cc = 4233$$

Due to the constraints present in SOLIDWORKS, the aforementioned data slightly deviated from original bore diameter and stroke length of 92 mm and 79.8 mm which yield an engine displacement of 4244 cc. The complete assembly of V8 crossplane engine capable of delivering an engine displacement of 4233 cc, slightly close to 4200 cc .

3.2 Material Properties for Parts used in Assembly

Following the Maserati F136 R engine design, the connecting rod, piston and piston rings were devised using AISI 52100 Steel with following properties:

Table 1: AISI 52100 Steel Properties

Property	Value	Units
Elastic Modulus	$2.1*10^{11}$	Nm^{-2}
Poisson's Ratio	0.30	-
Shear Modulus	$8*10^{10}$	N/m^2
Mass Density	7850	kg/m^3
Tensile Strength	$2*10^9$	N/m^2
Compressive Strength	-	N/m^2
Yield Strength	$1.5*10^9$	N/m^2
Thermal Conductiviy	0.2256	W/m-K
Specific Heat	1386	J/kg-K

Similarly, the crankshaft was devised using different material, being AISI 4130 Steel, normalized at 870°C with the materialistic properties as follows:

Table 2: AISI 4130 Normalized Steel at 870°C Properties

Property	Value	Units
Elastic Modulus	$2.05*10^{11}$	Nm^{-2}
Poisson's Ratio	0.285	-
Shear Modulus	$8*10^{10}$	N/m^2
Mass Density	7850	kg/m^3
Tensile Strength	$7.31*10^8$	N/m^2
Compressive Strength	-	N/m^2
Yield Strength	$4.6*10^9$	N/m^2
Thermal Conductiviy	42.7	W/m-K
Specific Heat	477	J/kg-K

3.3 Calculation for Application of Force on Pistons

For any engine, the pressure acting on piston head depends on several important factors such as compression factor and peak cylinder pressure which depends upon peak cylinder pressure/ For the case of Maserati F136 R 4.2 L (or 4233 cc) engine, the typical compression ratio is 11.3:1, with peak cylinder pressure as high as 60-100 bar during combustion at full throttle. At peak power corresponding to 395 hp, the pressure can be as high as 80-100 bar, respectively as 8-10 MPa. It is important to mention that the pressure generated due to combustion acts on individual piston head not on the entire assembly. With the bore diameter of 92 mm and peak pressure of 10 MPa, the force acting on individual piston can be calculated effectively using following formula:

$$F = P * A$$

Where

$$A = \frac{\pi * (0.092)^2}{4}$$

gives a value of 0.00665 m^2, which can be plugged in the above equation to evaluate the force. Assuming peak pressure of 10 MPa, the force can be evaluated as:

$$F = 0.00665 * 10000000 = 66500N$$

Hence a force of 66500 N or 66.50 kN acts on individual piston at full throttle.

3.4 SOLIDWORKS Model of Assembly

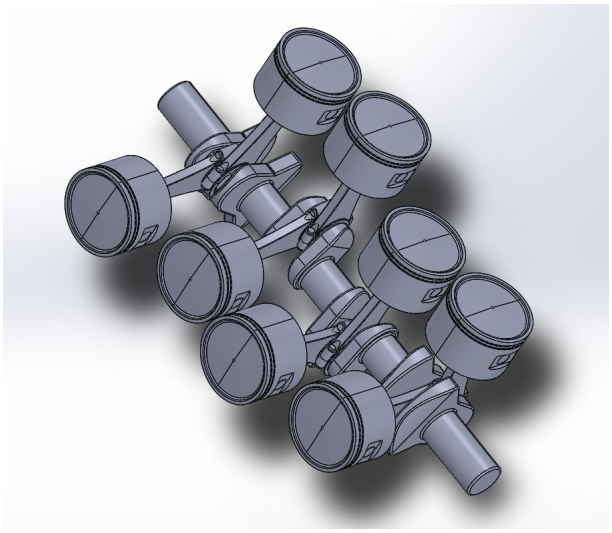


Figure 11: Crossplane V8 Engine (Isometric View)

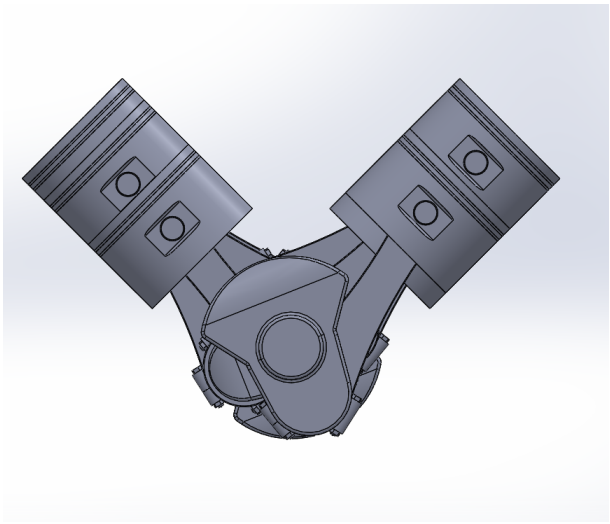


Figure 12: Crossplane V8 Engine (Side View)

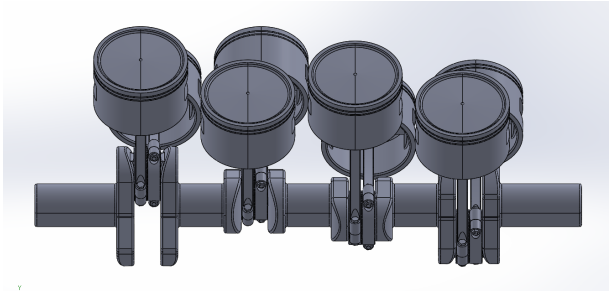


Figure 13: Crossplane V8 Engine (Side View(2))

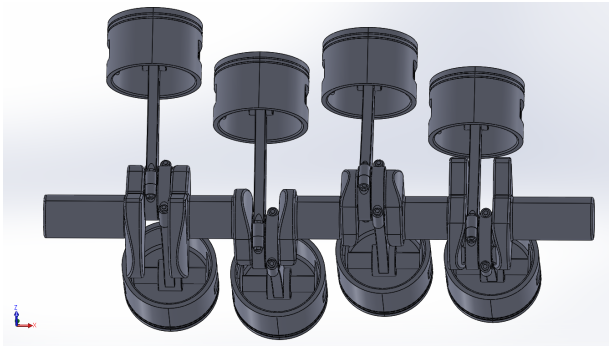


Figure 14: Crossplane V8 Engine (Bottom View)

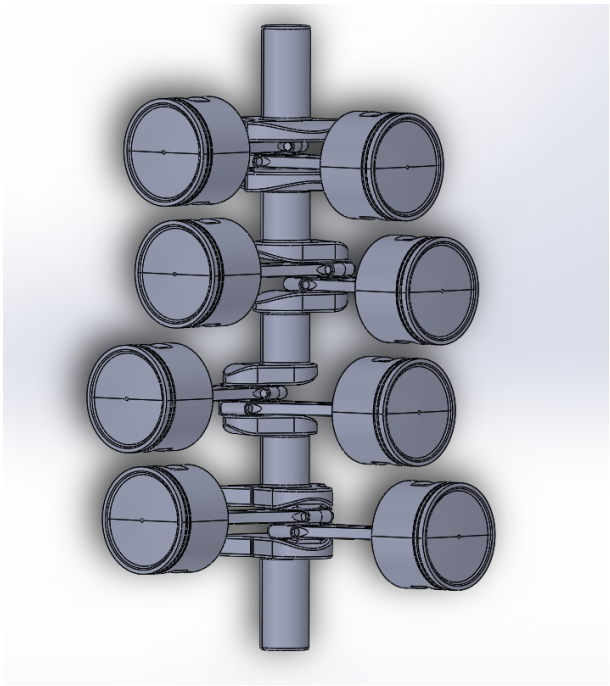


Figure 15: Crossplane V8 Engine (Top View)

3.5 Stress Analysis on Engine Assembly

For stress analysis, SOLIDWORKS 2021 has been brought into consideration. Although in the beginning Ansys Workbench 2024 Speos was taken into consideration but the student license limited the stress analysis on the entire assembly leaving behind SOLIDWORKS as an optimum interface for analysis. Significant effort was put to optimize the mesh which rendered unsuccessful. Using SOLIDWORKS, coarse quadrilateral meshing was taken into consideration. Coarse mesh was chosen to optimize the computational power as the hardware available could not accommodate a fine mesh configuration or simultaneously process all eight pistons. To address this limitation, the force application and boundary constraints were applied exclusively to the two pistons directly involved in the force calculations. This approach ensured that the simulation remained computationally feasible while maintaining focus on the critical interactions between the applied force and the selected pistons.

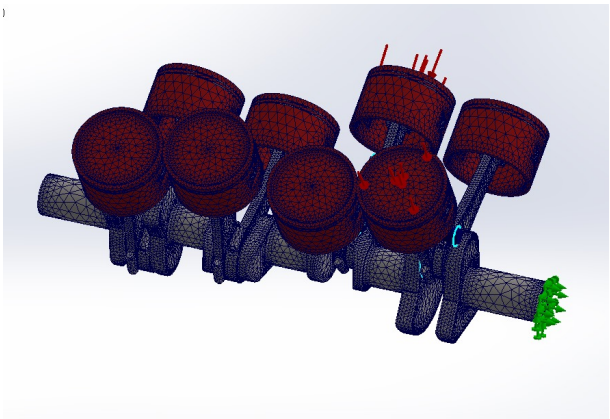


Figure 16: Mesh for Stress Analysis in SOLIDWORKS

Stress and strain analysis for the engine assembly was performed for two different ranges of pressure, respectively at 1450 psi and 500 psi, where 1450 psi corresponds to calculations provided in Section 3.3. Analysis was performed at 500 psi as well in order to understand the effect of reduced pressure on overall stress/strain and displacement concentration.

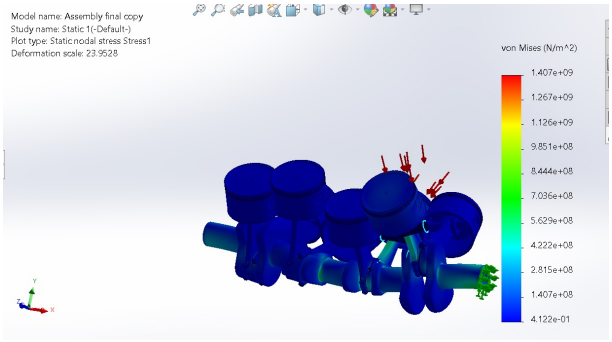


Figure 17: Stress Concentration at 1450 psi

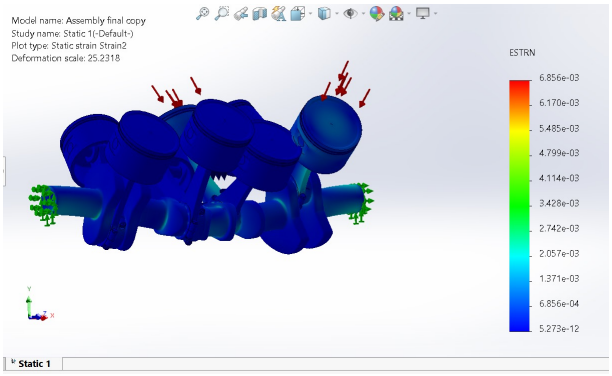


Figure 18: Strain Concentration at 1450 psi

In the analysis, the crankshaft has been supported by journal bearings at both ends. For pressure of 1450 psi, corresponding to equivalent force of 66500 N, the maximum value of stress was observed between the range of 422 MPa and 562.9 MPa, with greatest stress concentrated about the connecting rods and the pinned region of crankshaft. Due to the influence of high values of pressure, the moving parts tend to deform as time progresses until finally fracturing after surpassing endurance limits. As far as strain concentration is concerned, from the diagram it may be observed that the crankshaft has demonstrated buckling about the counterweight and journal mounting region. The typical strain value varies between 1.371 min/in and 2.057 min/in, where "m" stands for milli, the prefix of order $1*10^{-3}$. SOLIDWORKS has a built-in scale for demonstrating strains and deformation concentrated at regions. In such a circumstance, it scales up the deformation for better emphasis. Similarly, structural analysis was performed for 500 psi as well to correlate the effectiveness of analysis performed previously. Following figures depict the extent of stress, strain and displacement concentration respectively.

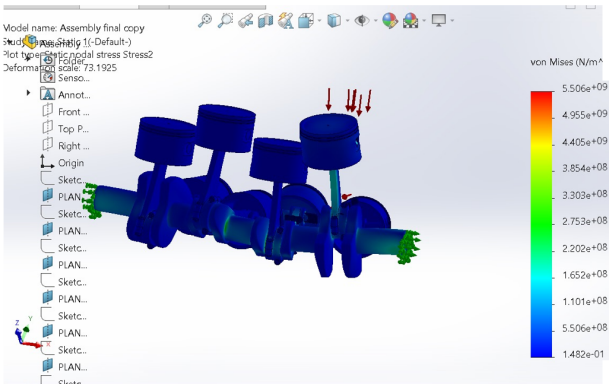


Figure 19: Stress Concentration at 500 psi

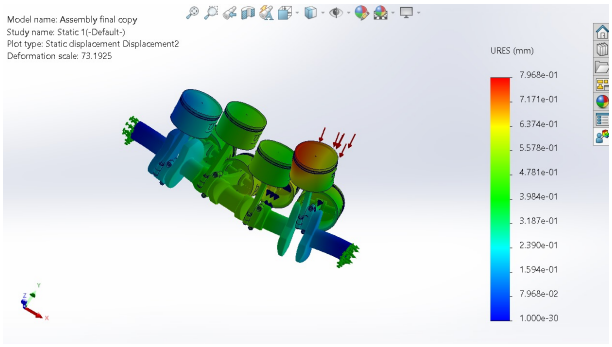


Figure 20: Displacement Concentration at 500 psi

Referring to the analysis of displacement and stress at pressure equivalent to 500 psi, it may be observed that decreasing pressure reduces the stress concentration about the body with maximum stresses being observed at critical regions such as fillets, sharp corners or areas of high stress concentration, which here exist about the main journal mounting and counterweights. Excessive loads/pressures acting on connecting rods lead to permanent failure after endurance has been crossed. It is necessary to mention that the deformation in SOLIDWORKS is always scaled up by the software itself merely for visualization. Application of pressure about the piston heads ultimately leads to uniform distribution, with major concentration directed at the center of crankshaft as pertained from Figure 20.

4 Discussions and Conclusion

Throughout the analysis, it has been observed that the following structural analysis falls more towards dynamic analysis than static analysis as the movement of the crankshaft has been restricted by means of fixed supports, which are actually responsible for producing deformation in the form of bending within the shaft. One primary reason of fixing the movement of crankshaft was had not it been fixed, the pistons would have displaced from their position. The analysis would have been much successful and robust had the dynamic environment taken into account rather than the present static environment.
The static analysis of structures like this assume constant applied load and time independence while ignoring inertia and damping effects. The deformation throughout is only calculated based on principles of equilibrium between applied forces and structural stiffness. In real world analysis, natural frequencies and oscillations influence the integrity of structure, which are simply ruled out in static analysis. Considering dynamic analysis, the effects of mass and damping are considered, which influence amplified deformation under time dependence/oscillatory loads. Moreover, time-varying loads such as impact, harmonic excitation induce transient responses and vibrational effects resulting in providing more clear information about consequent deformation. SOLIDWORKS offers three different dynamic analysis, respectively as frequency analysis, transient analysis and harmonic analysis, dealing with influence of natural frequency, analysis of deformation with respect to time and response to sinusoidal loads. On the broader perspective, this project has proved fruitful in understanding the working of engines in an effective manner and how structural failures arise over time due to continuous application of forces and pressure. In real world of engineering, it is necessary to design engine systems capable of delivering ultimate performance for long time period without excessive wear and tear and decrease in performance. This project has been aimed at amalgamation of modeling and analysis, which are fundamental in real world for optimization and improvements.

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Competing interests

All the authors agree to the data provided in the following project and all testify the authenticity of it.

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Supplementary Files (optional)

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