Sample Technical Report

Analysis of Cylinder Head Gasket Sealing Under Engine Operation Conditions

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Date Submitted: September 8, 2010

Declaration of Authorship

Note: The Declaration of Authorship form is to be submitted **separately** from the report can be found in the current technical report guidelines PDF.

Acknowledgments

I would like to thank my employers, the management team, and the Quality and Sales Department of Canada Rubber Group Incorporation in general but more particularly my supervisor NAME for technical techniques on testing, designing, and analysis of automotive and other related industrial gaskets.

A special acknowledgment and thanks to: NAME and NAME of the Department of Power Mechanical Engineering, National Tsing Hua University, Hsin Chu, Taiwan 300, ROC and to NAME and NAME of the Department of Research and Development, China Engine Corporation, Tao Yuan, Taiwan 337, ROC.

Abstract

To avoid the escaping gas from an engine affecting overall performance during operation, the proper pre-stressing force of the bolts and the gasket design are critical factors in enhancing the efficiency of the sealing of the gasket. The distribution of the contact pressure on the gasket and the stresses of the cylinder head at different loading conditions (cold assembly, hot assembly, cold start, hot firing) are explored by numerical calculations based on the finite element method. This research conducts parametric analyses for the pre-stressing force of the bolts and compares the differences between cold assembly and cold start conditions. The results reveal the efficiency of the head gasket sealing depends on the pre-stressing force of the hold-down bolts, without considernig any thermal stresses resulting from the temperature distribution in the cylinder head. The location of maximum contact pressure on the gasket is transformed when the thermal loading is taken into account.

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1.0 INTRODUCTION

This report is an investigation into the efficiency of engine gasket sealing and the stress/strain behavior of a 2.0 L cylinder head under various loading conditions using contact theory and thermal stress analysis. Parametric analyses of the pre-stressing force of bolts between cold assembly and cold start conditions are also discussed. The results of this report could be regarded as a design reference for the automobile engine.

The main idea of this analysis is to introduce the pre-tension element into the simulation of the bolted assembly with the other components. Compared with the traditional method, the pre-tension element has many advantages over the method of controlling the raising and lowering of the temperature.

Owing to the complicated engine structure and the lack of experimental data on engine performance, especially of the cylinder head, there is little literature available that fully discusses the structural analysis of the cylinder head. In this report, the commercial FEM software, ANSYS, is introduced into the numerical simulation of the structural analysis.

1.1.Gasket Function

A cylinder head gasket is required to affect a seal between the cylinder head and block of a gasoline or diesel engine. It is an integral component of the engine and is required to perform many functions at the same time during engine operation. The head gasket must maintain the seal around the combustion chamber at peak operating temperature and pressure. The gasket must seal against air, coolants, combustion and engine oil at their respective peak operating temperature and pressure. The materials used and design employed must be thermally and chemically resistant to the products of combustion and the various chemicals, coolants and oils used in the engine.

When assembled, the head gasket becomes an important part of the total structure of the engine. It supports the cylinder head along with its operating components. It must be able to withstand the dynamic and thermal forces that are transmitted from the head and block. The type of engine application will be the determining factor in cylinder head gasket design. With engines ranging in size from one-cylinder gasoline fired engines up to twelve cylinder, turbocharged or supercharged high-compression diesels, the material and design of the gasket is paramount to its functional life span.

1.2.Gasket Design

Every application requires a unique cylinder head gasket design to meet the specific performance needs of the engine. The materials and designs used are a result of testing and engineering various metals, composites and chemicals into a gasket that is intended to maintain the necessary sealing capabilities for the life of the engine.

The most widely used materials are as follows:

- Steel and stainless steel of various grades and forms.
- Fibre based composite materials.
- Graphite in various densities.
- Chemical formulations containing polytetrafluorothylene, silicone, nitriles, neoprene, polymeric resins and others.

Engines are designed to operate within a ‘normal’ temperature range of about 190 to 220 degrees F. A relatively consistent operating temperature is absolutely essential for proper emissions control, good fuel economy and performance.

If the engine overheats and exceeds its normal operating range, the elevated temperatures can cause extreme stress in the cylinder head, which may result in a head gasket failure. This is especially true with aluminium cylinder heads because aluminium expands about two to three times as much as cast iron when it gets hot. The difference in thermal expansion rates between an aluminium head and cast iron block combined with the added stress caused by overheating can cause the head to warp. This, in turn, may lead to a loss of clamping force in critical areas and cause the head gasket to leak.

1.3. Gasket Analysis

Both the design and the development of the automobile engine are complicated processes. To acquire the best performance of an engine in any operating condition, including harsh natural environments, many analytical tools and experimental methods are used to find the optimum parameters for engine design. However, numerous measured results point out that the gas escaping from the engine not only affects the output efficiency of the horsepower substantially, but also pollutes the environment. Therefore, the guarantee that the assembly between the cylinder head, bolts, and gasket is reliable and effective, through proper analytical procedures and tests becomes extremely important. Furthermore, the reduction of time and costs are considered in the development and design process of a new engine. The abovementioned reasons are critical deciding factors in whether the goals of a new engine being developed are achieved or not.

To solve these foregoing issues, the thermal and structural analyses must be adopted in the engine design to save the time of actual modifications. in addition, in order to allow for the thermal stresses, which need to be blended into the structural analysis of the engine, the heat transfer analysis must take place prior to the structural analysis in order to calculate the results under loading conditions, such as hot firing, hot assembly, etc.

Due to the interface between the cylinder head and the gasket, as well as the interface between the cylinder head and the bolts, contact behavior takes place. A finite element analysis with different displacement method is used as solution to deal with the contact problems. However, the temperature inside the engine structure is produced through various operating processes and loading conditions. Consequently, the mechanical problems of thermal contact need to be considered for the gasket sealing process.

2.0 BACKGROUND THEORY

2.1. The Contact Theory

The Contact Theory assumes that at some scale the contact surfaces between the cylinder head, bolts, and gasket are not completely flat. During assembly, intermetallic contact is made at the asperities across the surfaces. Initially the cylinder head gasket goes through a plastically deformation process until the entire contact force is supported. The size of the plastically deformed gasket region is directly proportional to the contact pressure and inversely proportional to the material hardness.

The main focus of this report is to explore the efficiency of gasket sealing. In accordance with the distribution of contact pressure on the gasket, the location of the minimum contact pressure can be determined. The possibility of gas escaping is extremely high in the region of the weakest contact pressure. This blow-by of gas causesa low engine compression ratio resulting in poor engine efficiency. For more information on Contact Theory see Appendix A.

2.2. Thermal Stress

Mechanical stress induced on a cylinder head gasket expands or contracts in response to changes in temperature. Such stresses caused by a temperature change are known as thermal stresses. Due to the analyses of the operating conditions for the engine, both the hot assembly and the hot firing are included in this research. Hence, a heat transfer analysis concerning the cylinder head must be carried out prior to the structural analysis. According to the principle of conservation of energy, the heat condition equation in the material can be expressed as given in Figure 1 below, where T is temperature:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0.$$

Figure 1: Heat Condition Equation

The temperature distribution in the material can be obtained with appropriate boundary conditions.

From the generalized Hooke's law, the strain components of the element including the thermal strains are as given in Figure 2 below, where ***σ*** is the normal stress, ***ε*** is the normal strain, ***E*** is the Young's modulus of elasticity, ***v*** is the Poisson's ratio, ***α*** is the coefficient of thermal expansion, ***ΔT*** is the incremental temperature, ***G*** is the shear modulus, ***τ*** is the shear stress, and ***γ*** is the shear strain.

$$\begin{aligned}
\varepsilon_x &= [\sigma_x - v(\sigma_y + \sigma_z)]/E + \alpha\Delta T. \\
\varepsilon_y &= [\sigma_y - v(\sigma_z + \sigma_x)]/E + \alpha\Delta T. \\
\varepsilon_z &= [\sigma_z - v(\sigma_x + \sigma_y)]/E + \alpha\Delta T. \\
\gamma_{xy} &= \tau_{xy}/G. \\
\gamma_{yz} &= \tau_{yz}/G. \\
\gamma_{zx} &= \tau_{zx}/G.
\end{aligned}$$

Figure 2: Equation for Strain Components of the Element

For more information on shear modulus see Appendix E. For more information on normal stress and normal strain see Appendix F. For more information on shear stress and shear strain see Appendix G.

Material properties of individual engine components are given in Figure 3 below.

	Young's modulus (Gpa)	Poisson's ratio	CTE (ppm/°C)	*k* (W/m-°C)
Exhaust valve (214N)	215	0.290	16.8	15.3
Inlet valve (EN52)	90	0.290	13.0	23.4
Cylinder head (Al alloy)	71	0.330	24.0	177.2
Cylinder block (Al alloy)	71	0.330	24.0	177.2
Liner (Cast iron)	107	0.295	11.7	0.0591
Bolt (SCM 435)	205	0.29	11.2	NA
Gasket	Multielastic	0.29	32	1.968E-4

Figure 3: Material Properties of Each Component of the Structural Analyses

After further calculation, the distribution of the contact pressure on the gasket and the strain/stress deformation of the entire structure can be obtained. See Figure 4 below.

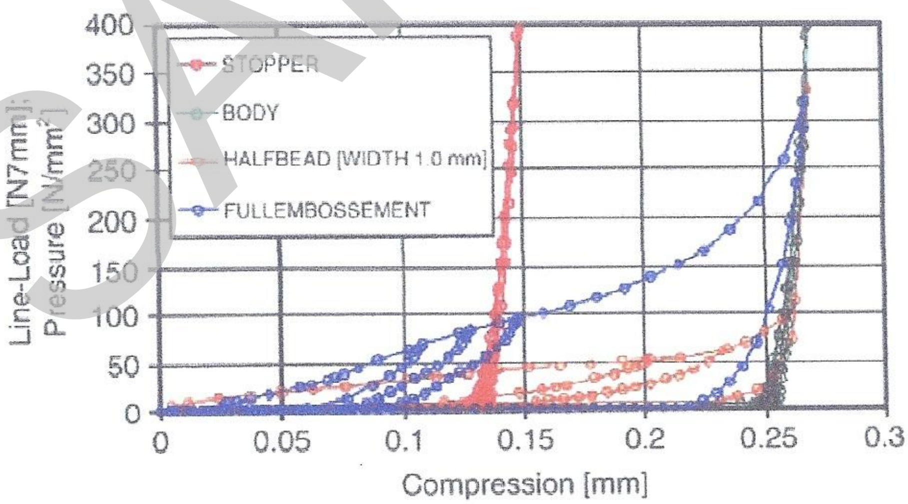


Figure 4: The Relation Between Pressure and Compression in the Gasket

3.0 METHODOLOGY

3.1. Finite Element Method

The Finite Element Method is a numerical analysis technique used to obtain solutions that are associated with physical and non-physical problems of cylinder head gasket sealing. The underlying premise of the method states that a complicated domain can be sub-divided into a series of smaller regions in which the differential equations are approximately solved. By assembling the set of equations for each region, the behavior over the entire problem domain is determined.

Each region is referred to as an 'element' and the process of subdividing a domain into a finite number of elements is referred to as 'discretization'**.** Elements are connected at specific points, called 'nodes'**,** and the assembly process requires that the solution be 'continuous' along common boundaries of adjacent elements.

The solution is determined in terms of discrete values of some primary field variables ϕ (e.g. displacements in **x**, **y** and **z** directions) at the nodes. The number of unknown primary field variables at a node is the degree of freedom at that node.

Once the element equations have been determined, the elements are assembled to form the entire domain **D**. The solution $\phi\ (x,\ y)$ to the problem becomes a piecewise approximation**,** expressed in terms of the nodal values of ϕ**.** A system of linear algebraic equations results from the assembly procedure.

3.2. Analysis Procedure

Stresses within the cylinder head gasket are as a result of external forces that act on the surface of the gasket (called 'surface forces') or forces that act throughout the volume (called 'body forces'). Under the influence of the applied forces, the gasket will deform. It is assumed that the gasket behaves elastically and returns to its initial configuration when the applied loads are taken away. A measure of the relative deformation of the solid body is referred to as 'strain'. In a Cartesian system, the components of strain are defined as shown in Figure 5 below:

$$\varepsilon_x = \frac{\partial u}{\partial x}, \quad \varepsilon_y = \frac{\partial v}{\partial y}, \quad \varepsilon_z = \frac{\partial w}{\partial z}$$

Normal Strains

$$\gamma_{xy} = \gamma_{yx} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}$$

$$\gamma_{xz} = \gamma_{zx} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}$$

$$\gamma_{yz} = \gamma_{zy} = \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}$$

Shear Strains

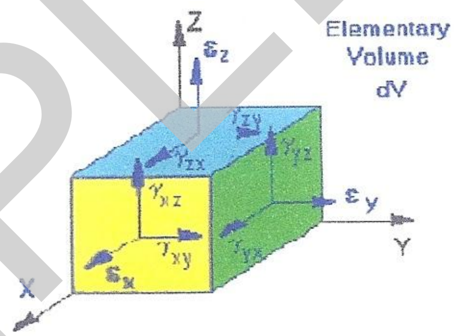


Figure 5: Components of Strain

At a given point, ***P***, within the body, the strain can be calculated as functions of the ***u, v***, and ***w*** displacement components. Assuming that the strains are sufficiently small such that second order terms can be neglected, this yields the strain displacement equations. The normal strains ***εx, εy,*** and ***εz*** are defined as the unit elongation of the body at a point in the direction of the respective ***x, y, z*** coordinate axes. The shearing strains measure the distort-ion of the angle between the various planes. For example, ***yxy*** measures the rotational distortion of the x-z and y-z planes. In general one can write the relationship in a matrix *form:* ***ε (x, y, z) = B δ (x, y, z).***

The state of stress can be denoted by the normal stresses ***σx, σy, σz,*** and six components of shear stress**.** In a Cartesian coordinate system, these components are configured on an element of volume as shown in Figure 6 below, and related to the strains by, Hooke's law, where ***E*** is the modulus of elasticity, ***V*** is Poisson's ratio, and ***G*** is the modulus of rigidity. The more general stress-strain relationship that allows for different material properties can be written in a matrix form: ***σ*** *(x, y, z)* = C ***ε*** *(x, y, z).*

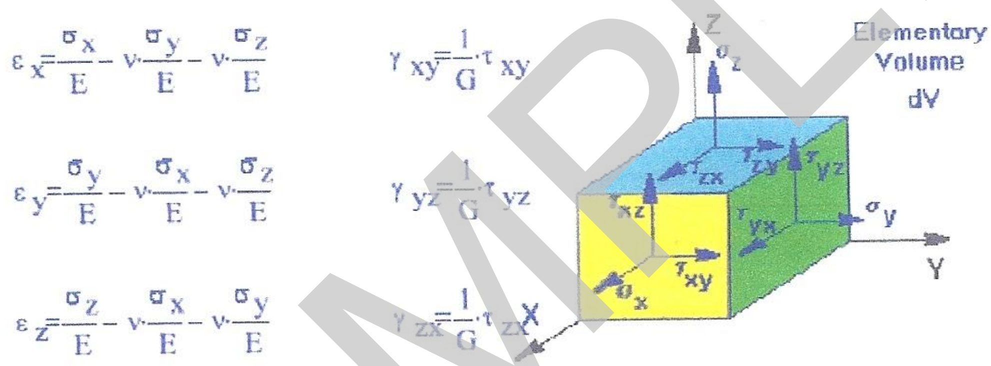


Figure 6: Normal Stresses and Shear Stress

3.3 Thermal Analysis

Thermal analysis is a form of analytical technique most commonly used in the branch of materials science where changes in the properties of materials are examined with respect to temperature. There are some assumptions concerning the thermal analysis of a cylinder head gasket which are as follows:

1. Owing to the fact that the coefficient of thermal conductivity of the gasket between the cylinder head and the block is extremely small, the gasket material

is adopted as being adiabatic. Because of this assumption, the structure of the engine above the gasket is modeled to be calculated by finite element analysis.

2. The components such as the bolt, valve guide, valve seat, and so on, contribute little to the heat transfer of the temperature distribution of the whole cylinder head. Therefore, besides the inlet valve and the exhaust valve, other components are neglected in the thermal analysis. The maximum temperature occurs at the highest operating speed. Hence, the maximum horsepower output at 6,500 rpm is considered in this report. The maximum temperature appears at the area around the spark plug, and the next one occurs at the location between two adjacent combustion chambers.

3.4. Structural Analysis

According to the applied loadings originating from different categories of mechanics, this linear-elastic analytical procedure could further be divided into three load steps by means of the superposition principle for simulating various operating processes of the engine. The final results of the structural analysis are composed of the outputs of these three load steps.

Assembly Loadings

The major percentage of the loading applied to the engine is the assembly loading. This mainly refers to the pre-stressing of the bolts, and it plays an important role in preventing gas from escaping from the internal part of the engine. In other words, in addition to the design of the gasket itself, the efficiency of the sealing of the gasket depends mainly upon the correctness of the pre-stressing of the bolts. In order to avoid an insufficient sealing of the gasket, the bolts are pre-stressed in the range of 28-32kN. In the case of the assembly loadings, the structure of the whole cylinder is approximately half symmetrical hence the structural symmetric planes should have symmetric displacement boundary conditions. In addition, the displacements of the nodes at the bottom of the block are fixed to avoid the rigid body motion.

Thermal Loadings

In the case of thermal loadings, the nodal temperatures resulting from the prescribed thermal analysis are assigned to all corresponding nodes of the FEM model of the second cylinder head in order to calculate the thermal stress/strain of the cylinder head structure.

Gas Pressure

The gas pressure created as a result of the firing of the spark plug is imposed on the surface of the combustion chamber. However, the magnitude of the gas pressure varies with different durations of the cycle. For the steady state analysis, the average gas pressure is introduced into the loading conditions for the numerical simulation of cold starts and hot firing.   For more information on gas pressure see Appendix B.

4.0 RESULTS AND DISCUSSION

4.1 Cold Assembly

When a head gasket is installed between the cylinder head and engine block, tightening the head bolts compresses the gasket slightly allowing the soft facing material on the gasket to conform to the small irregularities on the head and block deck surfaces. This allows the gasket to ‘cold seal’ so it won't leak coolant until the engine is started.
The head gasket's ability to achieve a positive cold seal as well as to maintain a long-lasting leak-free seal depends on several things: the ability to retain torque over time (which depends on the design of the gasket and the materials used in its construction), surface finish and the clamping force applied by the head bolts.
Some head gaskets remain resilient and retain torque better than others, so they do not require re-torquing. Others, though, can lose as much as 50 to 60% of their original torque after only 100 hours of service.

Even the best head gasket won't maintain a tight seal if the head bolts have not been properly torqued. The amount of torque that is applied to the bolts as well as the order in which the bolts are tightened determine how the clamping force is distributed across the surface of the gasket. If one area of the gasket is under high clamping force while another area is not, it may allow the gasket to leak at the weakly clamped point. The head bolts must therefore all be tightened in a specified sequence and equally torqued to a specified value to assure the best possible seal.

Another consequence of failing to torque the head bolts properly can be head warpage.

Uneven loading created by unevenly tightened head bolts can distort the head. Over a period of time, this may cause the head to take a permanent set. So any head that has not been properly torqued should be checked for flatness prior to installing a new head gasket.

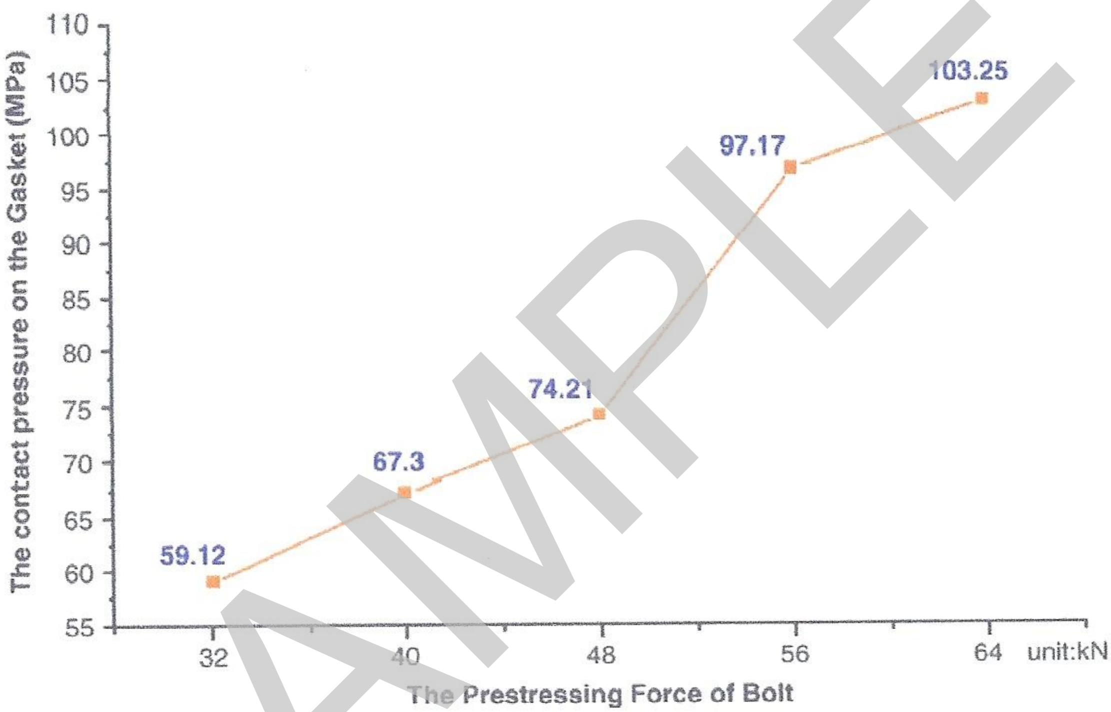


Figure 7: The Weakest Contact Pressure on the Gasket at Different Magnitudes of the Pre-Stressing Force (Cold Assembly)

The gasket sealing of the automobile in a motionless state is considered to be purely without any other external loading. Therefore, the maximum source of loading in this case is the pre-stressing of the bolts. In addition, the magnitude of pre-stressing the bolts with regards to dissimilar styles of engine structure and stroke volume is not identical. For this reason, the parametric analysis for the pre-stressing of bolts is implemented.

The result for the pre-stressing of the bolts with parametric analysis is shown in Fig.2. All analytical results in this case indicate that the weakest contact pressure on the gasket occurs at the same position and passes the safety factor of the design criteria (greater than 1.1 times the gas pressure). The contact pressure decays from 103.25 to 59.12MPa as the pre-stressing force of the bolt decreases from 64 to 32kN. It should be noted that the phenomenon of the efficiency of gasket sealing dependents mainly upon the magnitude of the pre-stressing force under cold assembly conditions. For more information see Appendix C.

4.2. Cold Starts

The cylinder head gasket is built from highly thermal and chemical resistant materials to ensure durability against the by-products of combustion and various chemicals that can rapidly cause its wear and damage. Since proper combustion pressure must be maintained on each cylinder, the head gasket will ensure that the air and fuel mixture are secured inside the cylinders so peak engine combustion is achieved. The operating condition of a cold start is simulated by means of the loading composed of both the assembly loading and the gas pressure.

The distribution of the contact pressure on the protruding portion of the gasket, and the position of the least effective gasket sealing are the same as with the condition of the cold assembly. According to the results shown in Figure 8, the rising of the lowest contact pressure from 39.94 to 70.34MPa depends on the increase of the pre-stressing force of the bolt.

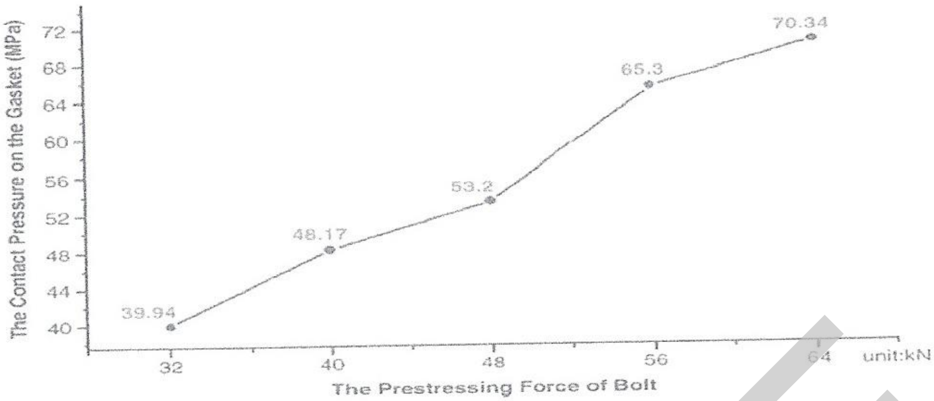


Figure 8: The Weakest Contact Pressure on the Gasket at Different Magnitudes of the Pre-stressing Force (Cold Starts)

Compared to the results of the cold assembly situation, the sealing capacity for the gasket diminishes substantially as a result of the active direction of the gas pressure being opposite to the pre-stressing force of the bolt as shown in Figure 9 below.

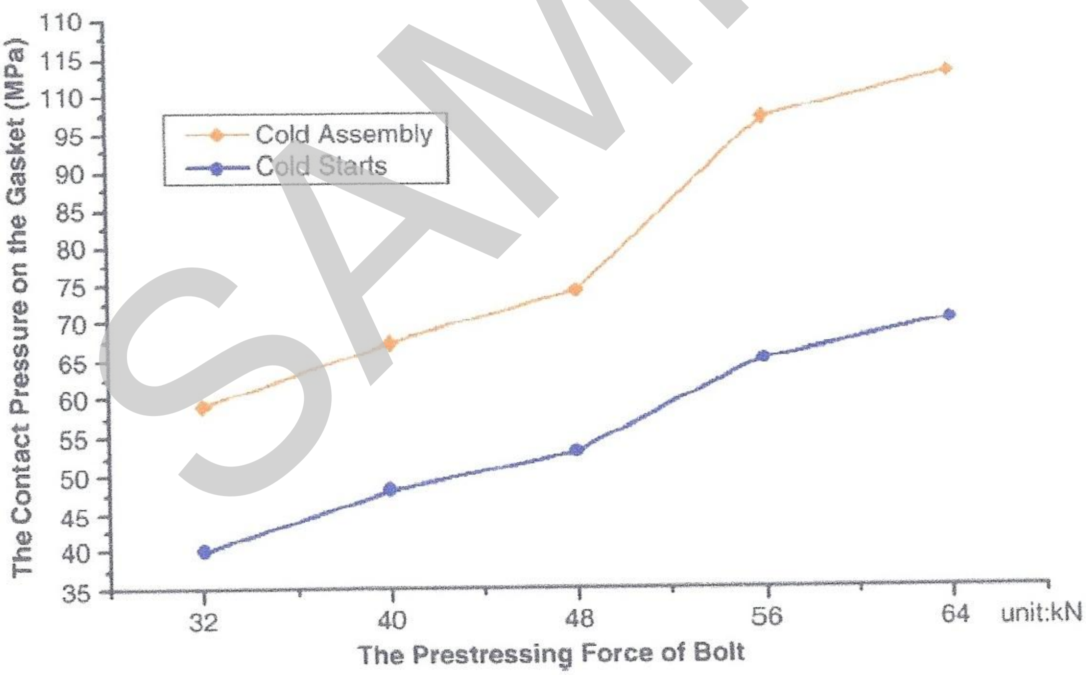


Figure 9: The Comparisons of the Weakest Contact Pressure Between the Operating Conditions of the Cold Assembly and Cold Starts

The analytical results also conform to the safety factor in spite of the reduction in sealing capacity.

4.3. Hot Assembly

The loadings made up by the pre-stressing force of the bolt and the thermal loading are used to simulate the state of thermal balance reached by the burst of gas being fired repeatedly. It should be noted that the thermal loading comes from the temperature distribution of the nodal result in the heat transfer analysis.

The analytical result shows that the distribution of temperature in the internal structure of the cylinder head has an influence on the distribution of the contact pressure on the gasket. The original position of the weakest contact pressure during cold assembly and cold starts becomes the maximum point as a result of the effect of thermal stress. In other words, the proper thermal stress could be used to improve the efficiency of gasket sealing through our proposed novel design, with relatively few engine components.
For more information see Appendix D.

4.4. Hot Firing

In the hot assembly, the operating process of hot firing is to simulate the moment of the spark plug firing. Therefore, in this case gas pressure is added into the applied loadings. The distribution of the contact pressure on the surface of the gasket is almost the same as the condition of the hot assembly except for the fact that the contact pressure is reduced. However, the sealing capacity of the gasket falls within the safety factor of the design criteria.

5.0 CONCLUSIONS

The structural analyses of a cylinder head under various loading conditions can be accomplished by means of the numerical simulation of finite element analysis. The main results combined with each analysis concerning the different operating processes of the engine can be separated into two parts as follows.

First, the capacity of gasket sealing mainly depends upon the pre-stressing of the bolts, which are the source of the maximum external loading on the inner structure of the cylinder head. In addition, the location of the weakest contact pressure on the raised portion of the gasket can be transferred as a result of the effect of thermal stress/strain.

In this investigation the analytical results indicate that the thermal stresses provide a positive support for the efficiency of gasket sealing. However, because of the opposite direction to the pre-stressing applied to the bolts, under the operating conditions with gas, the pressure will increase the possibility of gas escaping.

Therefore, an effective method was proposed to enhance the sealing capacity of the gasket by increasing the magnitude of the assembly force without exceeding the material strength of each component in the engine structure. At the same time, the structure of the gasket in the region of the worst sealing can be improved in the early stages of design. This is especially true for the raised portion.

Glossary of Terms

ANSY'S is a general purpose finite element modeling package for numerically solving a wide variety of mechanical problems. These problems include: static/dynamic structural analysis (both linear and non-linear), heat transfer and fluid problems, as well as acoustic and electromagnetic problems.

Engine block is a machined casting (or sometimes an assembly of modules) containing cylindrically bored holes for the pistons of a multi-cylinder reciprocating internal combustion engine.

Coefficient of thermal expansion is the degree of expansion of a material divided by the change in temperature. It varies with temperature.

Combustion chamber is recessed in the cylinder head and commonly contains a single intake valve and a single exhaust valve.

Contact theory is calculated by using the true contact area as a function of the applied load and surface roughness.

Cylinder head sits above the cylinders on top of the cylinder block. It consists of a platform containing part of the combustion chamber (usually, though not always), and the location of the poppet valves and spark plugs.

Elastic deformation is a change in shape of a material at low stress that is recoverable after the stress is removed.

Plastic deformation is when the stress is sufficient to permanently deform the metal.

Dicretization is also concerned with the transformation of continuous differential equations into discrete difference equations, suitable for numerical computing.

Dynamic force is the push or pull of an object that tends to produce acceleration of the body's motion in the direction of the force. It also changes the size and shape of a body.

Finite Element Method (FEM) is a numerical technique for solving models in differential form. For a given design, the FEM requires the entire design, including the surrounding region, to be modeled with finite elements.

Halfbead width of multi-layer-steel cylinder head gaskets takes charge of sealing of lubrication oil and coolant between the cylinder head and the block. Since the head lifts off periodically due to the combustion gas pressure, both the dynamic sealing performance and the fatigue durability are essential for the gasket. A finite element model of the halfbead has been developed and verified with experimental data. The half-bead forming process was included in the model to consider the residual stress effects.

Line-load magnitude represents a FORCE per UNIT LENGTH (e.g. kNlm) when considering the out-of-plane dimension of the model.

Modulus of elasticity the ratio of the stress applied to a body or substance to the resulting strain within the elastic limit.

Structural analysis is a process to analyze a structural system in order to predict the responses of the real structure under the excitation of expected loading and external environment during the service life of the structure. The purpose of a structural analysis is to ensure the adequacy of the design from the view point of safety and serviceability of the structure

Thermal analysis is a branch of material science where the properties of materials are studied as they change with temperature

Thermal loading is sum of all the factors, which tend to increase body temperature.

Thermal stress is mechanical stress induced in a body when some or all of its parts are not free to expand or contract in response to changes in temperature.

List of References

[1] E.A. Wilson, B. Preson, Finite element analysis of element problems using different displacement, Int. J. Numer. Meth. Eng. 2 (1) (1970) 387-395.

[2] S.K. Chan, I.S. Tuba, A finite element method for contact problems of solid bodies part-I, theory and validation, Int. J. Mech. Sci. 18 (13) (1971) 615-625.

[3] S. Ohte, Finite element analysis of elastic contact problems, Bull. JSME 16 (95) (1973) 797-804.

[4] C.V. Medhusudana, L.S. Fletcher, Contact heat transfer-the last decade, AIAA J. 24 (3) (1985) 510-523.

[5] A.R. Mijar, J.S. Arora, Review of formulations for elastostatic frictional contact problems, Struct. Multidiscip. Optim. 20 (2000) 167-189.

[6] T. Belytschko, M.O. Neal, Contact-impact by the pinball algorithm with penalty and Lagrangian methods, Int. J. Numer.Meth. Eng. 31 (3) (1991) 547-572.

[7] S.W. Chyuan, Finite element simulation of a twin-cam 16-valve cylinder structure, Finite Elem. Anal. Des. 35 (2000) 199-212.

[8] L.Yong, R.D. Reitz, Modeling of heat conduction within chamber walls for multidimensional internal combustion engine simulation, Int. J. Heat Mass Transfer 41 (6,7) (1998) 859-869.

[9] J. Montgomery, Methods for modeling bolts in the bolted joint, ANSYS User's Conference, 2002.

[10] Jonathan, Modeling diesel engine cylinder head gaskets using the gasket R material option of the SOLID185 element, ANSYS User's Conference, 2002.

[11] S.Yasumasa, Analysis of gasket flanges with ordinat elements using APDL control, ANSYS User's Conference, 2000.

[12] J.C. Simo, T.A. Laursen, An augmented Lagrangian treatment of contact problems involving friction, Comput. Struct. 42 (1) (1992) 97-116.

[13] T. Belytschko, W.K. Liu, B. Moran, Nonlinear Finite Elements for Continua and Structures, Wiley, New York, 2000, pp. 569-613.

[14] C.C. Lee, K.N. Chiang, W.K. Chen, R.S. Chen, Design and analysis of temperature distribution for 2.0 L cylinder head in engine operation, in: The 20th National Conference on Mechanical Engineering, CSME, Taipei, Taiwan, 2003.

APPENDIX A: Contact Theory

Generally speaking, penalty methods like the Lagrange multiplier methods and augmented Lagrangian method are widely used in the mechanical contact finite element simulation. However, the penalty methods suffer from ill-conditioning that worsens as the penalty values are increased. The Lagrange multiplier method introduces extra unknowns, and the resulting equation system is not necessarily positive-definite. The augmented Lagrangian method combines the penalty methods and the Lagrange multiplier methods, and inherits the advantages of both methods. The variational weak form of the augmented Lagrangian method on the contact region (rc) could be expressed as:

$$\delta\pi = \int_{\Gamma_c} \delta\left(\lambda\gamma_N + \frac{\alpha}{2}\gamma_N^2\right) \mathrm{d}\Gamma, \qquad (1)$$

where **λ** is the Lagrange multiplier. a is the penalty value and *yN* is the interpenetration rate of two contact bodies. Through the variational calculation, Equation (1) could be transformed to its relative strong form as:

$$Ma + f^{\mathrm{int}} - f^{\mathrm{ext}} + G^{\mathrm{T}}\lambda + P_C d = 0. \qquad (2)$$

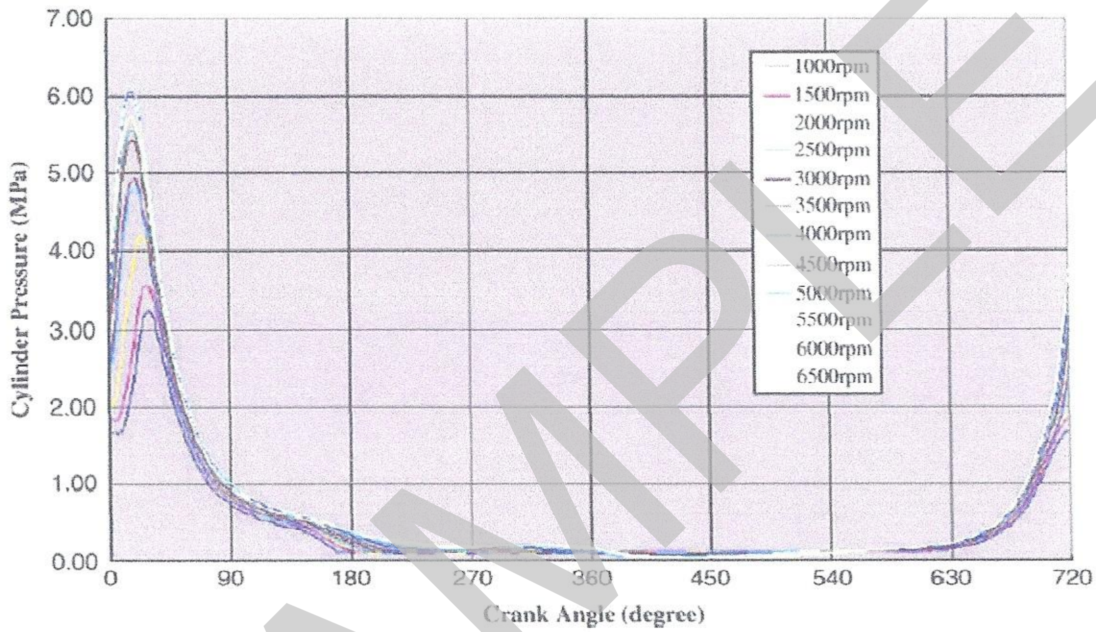
$$Gv \leq 0. \qquad (3)$$

where ***v*** refers to the velocity field in both bodies; the Lagrangian multiplier is denoted by **λ,** and ***GTA*** is the contact force; the contact stiffness is denoted by ***PC,*** and ***PCd*** is the contact force (penalty force). The **fint**, ***f*****ext** and ***Ma*** are the internal, external and inertial forces, respectively. Equation (2) is the governing equation of the contact finite element computation. Equation (3) is the inequality constraints that describe the contact boundary of two contact bodies.

The chief benefit of the augmented Lagrange method for the contact problem is that it provides the robustness and stability for the penalty method, while at the same time being a simple procedure that does not involve additional equations for the discrete system. To accurately simulate the contact behaviour between the cylinder head and the gasket under various conditions of engine operation, the augmented Lagrangian method is adopted in the finite element analysis.

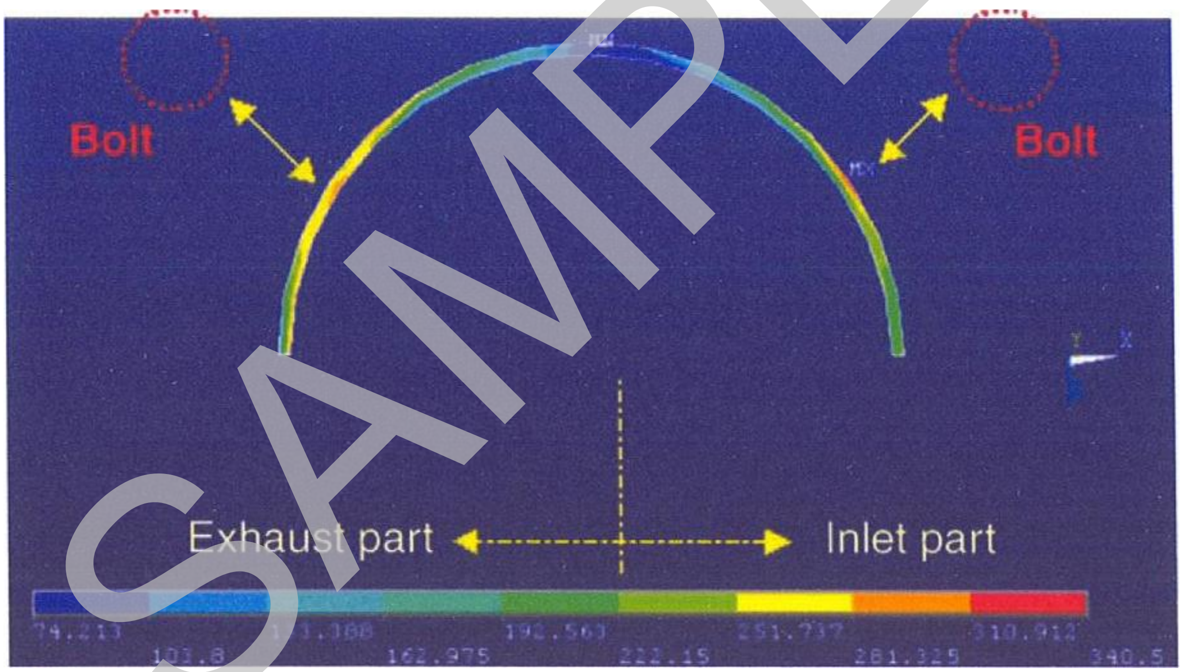
APPENDIX B: Gas Pressure

In this report, the maximum average gas pressure, 6.7MPa, produced at a higher speed during the operating process of the engine is expected to substantially reduce the efficiency of the gasket sealing. The gas pressure of the 2.0 L engine at different cycle durations at specific operation speeds is illustrated in the diagram below.



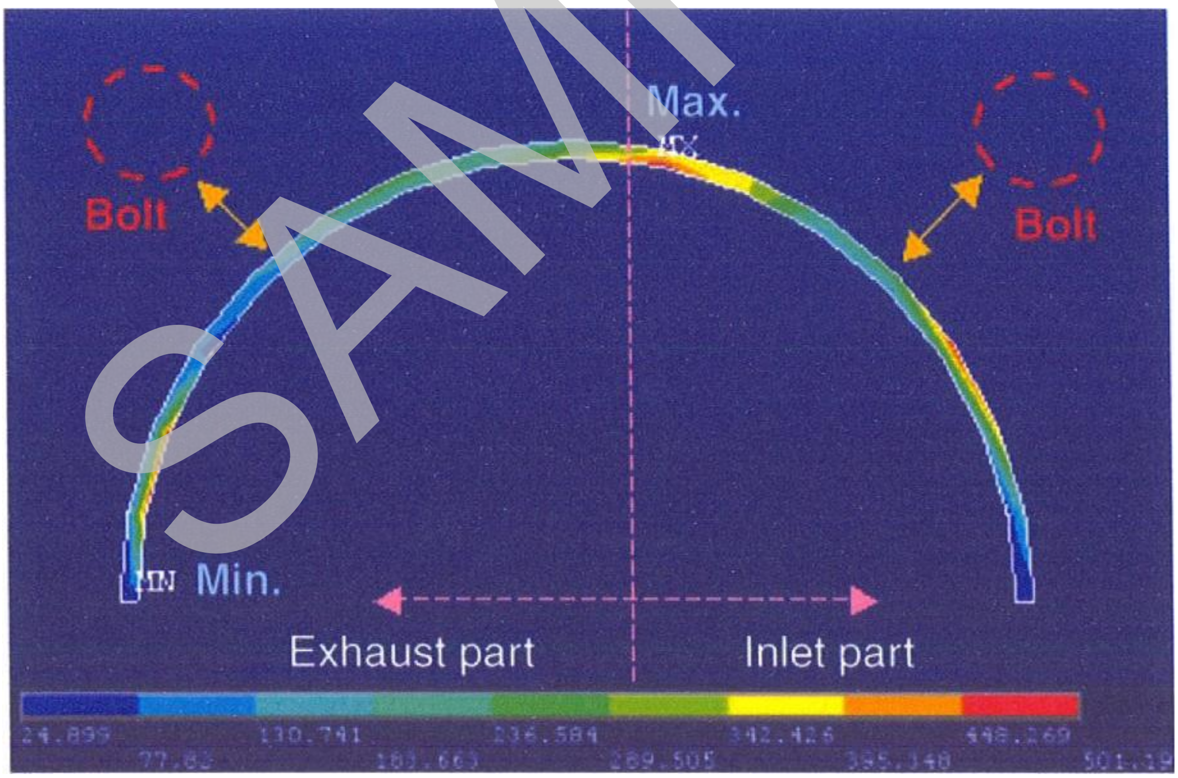
APPENDIX C: Cold Assembly

The diagram below illustrates the distribution of the contact pressure on the gasket (pre-stressing of bold: 48 kN). The results clearly reveal that the weakest contact pressure on the gasket appears at the raised location of the inner ring between two adjacent combustion chambers. This situation results from the fact that the distance between the bolts and the foregoing location on the gasket is the greatest. Moreover, the maximum contact pressure on the surface of the gasket at the inlet part is slightly different from the exhaust part by virtue of the structural asymmetry.



APPENDIX D: Hot Assembly

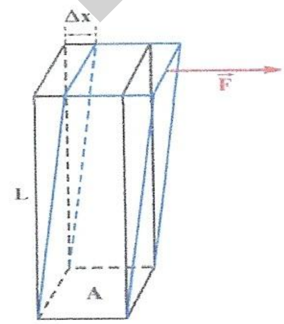
The diagram below shows the distribution of the contact pressure on the gasket (pre-stressing of bolts: 32 kN). The analytical result shows that the distribution of temperature in the internal structure of the cylinder head has an influence on the distribution of the contact pressure on the gasket. The original position of the weakest contact pressure during cold assembly and cold starts becomes the maximum point as a result of the effect of thermal stress in hot assembly. In other words, the proper thermal stress could be used to improve the efficiency of gasket sealing through our proposed novel design, with relatively few engine components.



APPENDIX E: Shear Modulus

The shear modulus is the elastic modulus we use for the deformation which takes place when a force is applied parallel to one face of the object while the opposite face is held fixed by another equal force. When an object like a block of height ***L*** and cross section ***A*** experiences a force ***F*** parallel to one face, the sheared face will move a distance ***Δx****.* The shear stress is defined as the magnitude of the force per unit cross-sectional area of the face being sheared *(F/A).* The shear strain is defined as ***Δx/L.*** The shear modulus **S** is defined as the ratio of the stress to the strain.

$$S \equiv \frac{\text{shear stress}}{\text{shear strain}} = \frac{\frac{F}{A}}{\frac{\Delta x}{L}} = \frac{F\,L}{A\,\Delta x} \quad \text{(units are Pascals)}$$



The bigger the shear modulus the more rigid is the material since for the same change in horizontal distance (strain) you will need a bigger force (stress). This is why the shear modulus is sometimes called the modulus of rigidity.

APPENDIX F: Normal Stress and Normal Strain

Imagine that a small bar along the ***z*** direction is isolated from a solid body, as shown in the equation below. The force in the ***x*** direction per unit area on the ***x*** facet is denoted as ***σx*** a normal stress:

$$\sigma_x = \frac{F_x}{S_x}, \qquad (F.1)$$

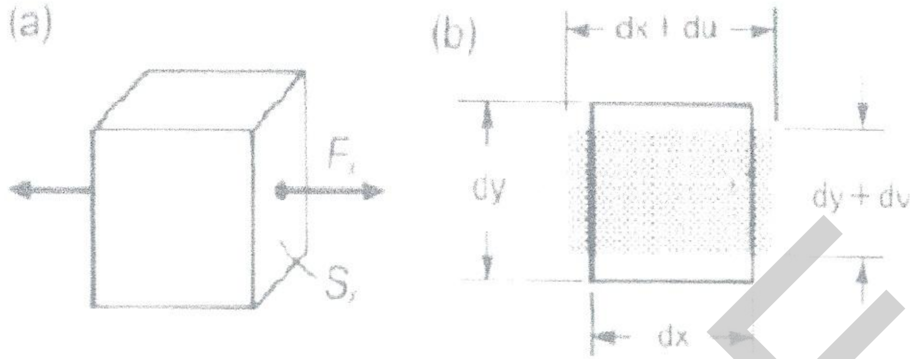
A body under stress deforms. In other words, a strain is generated. With a normal stress ***σx*** the bar elongates in the ***x*** direction. The standard notation to describe strain is by introducing displacements ***u, v,*** and ***w***, in the ***x, y,*** and ***z*** directions, respectively, as shown in the equation below. The dimensionless quantity is called the unit elongation, which is a component of the strain tensor.

$$\epsilon_x = \frac{\partial u}{\partial x} \qquad (F.2)$$

Hooke's law says that the unit elongation is proportional to the normal stress in the same direction where the quantity **E** is the Young's modulus.

$$\epsilon_x = \frac{\sigma_x}{E}, \qquad (F.3)$$

Under the same stress ***σx*** the ***y*** and ***z*** dimensions of the bar contract:



In the diagram above: (a) the normal force per unit area in the *x* direction is the ***x*** component of the stress tensor; and (b) the normal stress causes an elongation in the ***x*** direction and a contraction in the ***y,*** and **z** directions.

$$\epsilon_y \equiv \frac{\partial v}{\partial y} = -\nu \frac{\sigma_x}{E}, \qquad (F.4)$$

$$\epsilon_z \equiv \frac{\partial w}{\partial z} = -\nu \frac{\sigma_x}{E}. \qquad (F.5)$$

This effect was discovered by Poisson**,** and the dimensionless constant ***v*** is called 'Poisson's Ratio'. For most materials, *v =0.25.*

APPENDIX F: Shear Stress and Shear strain

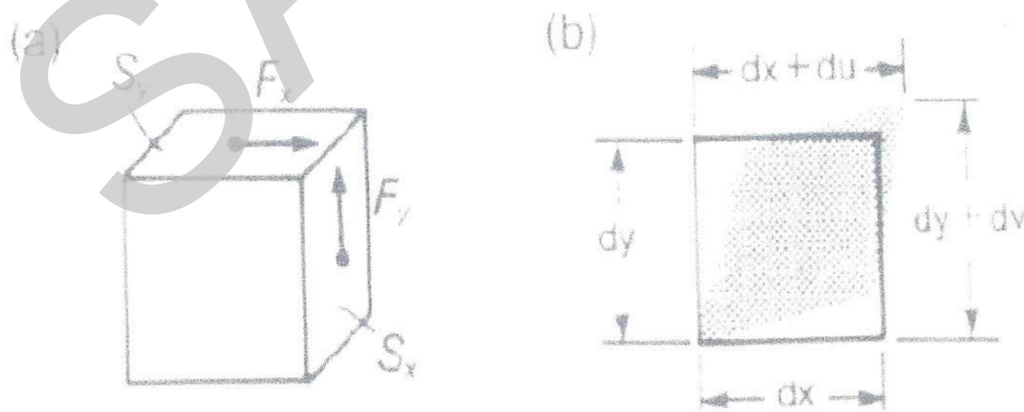
The ***x*** component of the force per unit area on a facet in the ***y*** direction is denoted as ***Txy*** and is called a component of the shear stress:

$$\tau_{xy} = \frac{F_x}{S_y} \qquad (F.6)$$

The condition of equilibrium, that is, the absence of a net torque on a small volume element, requires that ***Txy = Tyx***. *A* shear stress causes a shear strain, defined as:

$$\gamma_{xy} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \qquad (F.7)$$

The relation between shear stress and shear strain can be established based on the relation between normal stress and normal strain. Actually, by rotating the coordinate system 45 °, it becomes a problem of normal stress and normal strain.



In the diagram above: (a) the shear force per unit area is a component of the stress tensor; and (b) the shear stress causes a shear strain.

$$\tau_{xy} = \frac{E}{2(1 + \nu)} \gamma_{xy} = G\gamma_{xy} \qquad (F.8)$$

The quantity ***G = E/2(1 + v)*** is called the modulus of elasticity in shear.