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FINITE ELEMENT ANALYSIS AND EXPERIMENTAL STUDIES ON RIVETS AND RIVETING OF BRAKE LININGS

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ABSTRACT: The behavior of brake lining friction material under various loading conditions were studied using laboratory test equipment and test procedures. The experimental study was carried out to find out optimum parameters involving in the riveting of linings for the attachment with brake shoes. Finite element analysis was carried out using FEAST software package (developed by VSSC, Thiruvananthapuram) to evaluate the deformation of rivet as well as riveted assembly. The stresses and deflection contours were obtained for various designs by changing the crimp height. From theoretical approach the safety factor of the lining was evaluated. The theoretical and experimental results were compared to obtain optimum design parameters.

INTRODUCTION

It is known that friction materials have mechanical strength and thermal expansion properties which vary with fiber orientation. Messer Anderson and Knapp assumed that for friction material structural analysis [1] a suitable multi axial strength criterion should be developed and carried out research at Ford Motor Company on brake lining mechanical properties. The research paper describes Thermomechanical Analysis (TMA) used for the measurement of dimensional changes of sample, sample preparation effects, lining composition, processing effect, friction material rivet studies, load deflection characteristics and finite element modeling for rivets and shoes as well as complete shoe and lining assemblies. In the present study, Finite Element Modeling of friction material in the area around a rivet was carried out to evaluate the stress field for brass and steel rivets with different rivet head configurations.

For the problem involving complex shapes and complicated boundary conditions, the finite element method is used to find out the stress field deflection. The finite element analysis was used to find out stresses and deflection of friction material under the rivet head during riveting. For this purpose, the finite element model of friction material under the rivet head was created and it was analyzed in static condition. The lining was modeled with various crimp height and stress contours were obtained by applying the drag forces.

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Due to the orthotropic behavior of friction material, strength and moduli were evaluated along the fiber orientation as well as normal to the fiber orientation. As the first step the load deflection characteristics of the friction material were obtained experimentally, to do the analysis.

The tubular and semi tubular rivets are commonly employed for riveting lining with the shoes. The three factors to be considered for rivets and riveting are the type of rivet material, amount of setting force and the type of rivet head configurations. All these three parameters were considered for the analysis.

For the present studies, the strength of the attachment of the lining with the shoes were found out with various setting force as well as with different types of rivets.

MECHANICAL PROPERTIES OF BRAKE LININGS – LABORATORY STUDIES

The various mechanical properties required for analysis are the compression strength, shear strength, tensile strength, coefficient of thermal expansion, mass density of the material and the elastic moduli. To evaluate each property, appropriate testing equipment and test procedures were selected. While preparing the samples the direction of fibers was considered as an important factor to avoid variation in the obtained results. The results obtained by experiment and finite element method were compared to get an idea about the role of rivet and riveting on the performance of the product.

The load deflection graph was also obtained during testing of samples in the universal testing machine and the stress-strain diagrams were plotted from those graphs.

COMPRESSION TESTING

During riveting, the area under rivet head is compressed between the steel shoe and rivet head and during the braking the whole lining is under compression along the normal direction. Since the drag force is acting along the transverse direction after the braking, the evaluation of compression strength in all these three directions (normal, longitudinal and transverse directions) is important for this analysis and this was done by changing the direction of application of loading. The sample size was maintained as 12.70X12.70X25.40 mm for the compression testing.

A typical load verses deflection graph of the heavy-duty brake lining under transverse compression loading is shown for reference in Figure 1.

The compression strength data of the heavy-duty brake ling block shows that the normal compression strength is higher than that of both longitudinal as well as transverse compression strength.

SHEAR STRENGTH TESTING

For the shear strength evaluation, the specimen was made as a square block with 10 mm thickness and the cross-section area was maintained as 250 mm^2. The standard samples size was loaded using a thin shear plane to provide some representative value of the lining internal shear strength. From the literature [1], it is known that this is the most often chosen test strategy for lining shear tests. The shear strength is expected to be strongly dependent upon the orientation of the reinforcing fiber, fiber type and concentration, and integrity of the fiber matrix bond.

TENSILE STRENGTH TESTING

From the literature as well as experimental studies, it was found that the friction material is weakest under tension. Since the unloaded friction material is under tension during riveting and after riveting, the evaluation of tensile strength is more important for this analysis.

The length of the tensile test specimen was limited in the range of the width of the lining. The cross-sectional area of the specimen was kept as 175 mm^2 for better holding in the specimen and to make the testing easier. Due to brittle nature of brake lining, the tensile strength of the lining wasb12 to 15 N/mm^2.

MASS DENSITY OF THE MATERIAL

The mass density of the material was evaluated from the specific gravity data. Mass density was found to be in the range of 1.94 gm/cc to 2.14 gm/cc

ELASTIC MODULUS

Elastic modulus of the lining under compression loading was only considered for this analysis.

It is reported in the literature [7] that the elasticity modulus of friction materials will vary between 16.50 $N/mm^2$and 120 N/mm^2 for soft and hard linings. The elastic modulus under tensile loading was much higher (in the range of 3000 N/mm^2 to 3500 N/mm^2) than the elastic modulus under compression loading.

The other material properties like coefficient of thermal expansion, swell etcetera were also determined.

RIVETING OF LININGS – EXPERIMENTAL STUDIES

The semi tubular rivets are commonly employed for the attachment of lining with the shoe. For experimental studies the setting force and rivet material are the two factors considered for riveting. The proper setting loads require consideration of the rivet clinching requirements and the strength of the friction material in compression.

The factors to be considered for applying the setting force are (1) excessive setting force may crack the friction material and (2) insufficient setting force will not adequately hold the lining on to the shoe.

To evaluate the optimum setting force by considering above two factors, the range for the setting force was fixed between 9.50 K.N. to 21.50 K.N. While riveting the lining, a load deflection graph was also recorded. For the present experimental studies, steel and brass rivet with taper head was used.

From the load deflection curves, it is possible to determine the various stages of rivet deformation defined below.

1. Seat plunger
2. Flare
3. Roll back flare
4. Solid shank compression.

While applying setting load, in the first stage the lead is transmitted to the rivet alone and causes deformation in the tubular portion of the rivet shank. It starts flaring to touch the shoe and after that the deformation of the tubular shank is known as roll back flare.

Once the rivet clinch is rolled back to contact the shoe, nearly the additional force acts to compress the friction material, unless the rivet shank buckles and causes significant friction between rivet shank and shoe. Still some force is required to deform the rivet, relative to the force required to compress the lining. Thus, if the force due to friction between rivet shank and shoe is low, the incremental load deflection characteristics of the assembly can be considered primarily due to the lining compression behavior.

A typical lead deflection curves for brass and steel rivets during riveting of lining is presented in Figure 2. The behavior of rivet material under riveting setting force can be well understood from the load deflection curves. Both steel and brass riveting load deflection curves are having varying slopes. For a brass rivet, the load taken for flare and roll back flare is approximately 7 K.N. and the remaining load is used for solid shank compression. However, for a steel rivet the load is transferred to the solid shank only above 9.50 K.N. The solid shank compression is a very easy process and occurs very fast and therefore careful control of setting force is required at this stage. Otherwise, once the setting force reaches the diameter of the rivet hole, it will cause crack in the lining and lead to failure.

The improper selection of rivet for a particular application will cause some errors in riveting stage itself and the details about the common errors in riveting is given in Table 1.

Table 1. Common riveting errors

Conditions	Riveting Error
1. The rivet is too long	Buckled shank or the clinch may not contact the shoe and provides no clamping load to the lining
2. Counterbore depth is too deep	
3. Too short rivet	Failure of friction material
4. Shallow depth of counterbore	
5. Excessive setting force	

Optimum setting force is normally preferred to have proper friction between the lining and the shoe. But it is limited by the normal compression strength and tensile strength of the lining material.

RIVETING PARAMETERS

The riveting parameters namely the clinch diameter, clinch height, cinch allowance, clearance between lining rivet hole and rivet shank were determined for each setting force. The clearance is filled to better extend at the setting force of 1800 KGS for the brass rivets (bulging to 6.72 mm). With the same setting force, the bulging of steel rivet was observed as 6.60 mm.

RIVET HOLDING STRENGTH – RESULTS AND DISCUSSION

Table 2 gives the rivet holding strength (RHS) data of the linings with brass and steel rivet with tapered head.

EXPERIMENT	SETTING FORCE (KGS)	BRASS RIVET (KGS)	STEEL RIVET (KGS)
1	1200	465	415
2	1400	565	545
3	1600	585	625
4	1800	595	635
5	2000	520	505
6	2200	515	340

1. Steel riveted linings shoes are having higher rivet holding strength than brass riveted linings shoes. From Table 2, it’s clear that the steel riveted linings shoes are having marginally higher rivet holding strength than the brass riveted linings shoes respectively 635 and 595 at a setting force of 1800 KGS. The normal deformation of steel rivet was found to be marginally less compared to brass rivet respectively at 6.72 mm and 6.60 mm.
2. During flaring greater load is taken by brass rivet compared to steel rivet.
3. The rivet holding strength for brass rivet shows better optimum range compared to steel rivet. Therefore, this could minimize the problems arising out of the usage of

improper setting forces. However, the steel rivet attains a peak rivet holding strength at one point and shows greater variations in RHS.

4. For both steel and brass rivets, the maximum rivet holding strength occurred between 1600 KGS to 1800 KGS setting force. To increase the safety factor, the setting force cannot be fixed at the load in which maximum RHS was observed. Therefore, the setting force of 1600 KGS was found to hold good for its dynamic performance.

FINITE ELEMENT METHOD

With the advent of computers, one of the most powerful techniques that has been developed in the realm of engineering analysis is the finite element method. For solving a problem which has complex shapes and complicated boundary conditions, finite element approach is mainly adopted. In this method the whole structure is divided into a few finite elements with small sizes. The method provides only an approximate solution but an acceptable solution. The module used for all these model generations was Pre-Win 2.0. It produces ready-to-run data for the finite element calculations and enables to analyze the results for interpretation. FEAST-C (Finite Element Analysis of Structures – Composites) was the package used for analysis. It was developed by Vikram Sarabhai Space Center, Thiruvananthapuram.

FINITE ELEMENT ANALYSIS ON RIVETING

The effect of various parameters involving in the riveting process like setting force, rivet material selection, rivet head configuration etcetera cannot be readily determined experimentally. So, an analytical approach was tried to find out the optimum parameters.

A single riveted assembly consists of non-asbestos lining, steel shoe and steel or brass rivet was modelled using the preprocessor module. The analysis was carried out in four stages.

Stage 1: To find out he stress distribution under the taper head and flat head rivet, the setting force was uniformly applied under the rivet heads using the uniform brick load option.

Stage 2: In the above model, the setting force ranging from 1200 KGS to 2000 KGS was applied and the results were compared.

Stage 3: The drag force was calculated and applied on the rivet hole. The lining was modeled with various crimp heights. Stress and deflection contours were obtained, and the safety factor was evaluated.

Stage 4: Brass and steel rivets were designed, and the deformation patters were analyzed with various setting forces for comparing the radial and longitudinal deformations.
An assumption was made that the friction material behaves elastically. From the deflection pattern, the failure points can be identified by looking for the maximum deflection. For this study, no slip was allowed between rivet head and friction material or at the friction material

to shoe interface. Further simplifying the analysis, the assumptions were made that the shoe is rigid, that the lining does not contact the rivet shank and that the friction material exhibits orthotropy. Lining orthotropy was modelled using different elastic moduli in the direction normal to or in the plain of reinforcing fibers.

While considering the setting force, the deflection patterns were obtained for a range of 1000 KGS to 2000 KGS with different rivet head configurations and different materials. The flat head and tapered head configurations and brass as well as steel rivet materials were considered for the finite element analysis, in addition to the setting force. From the experimental study only, it was possible to find out the maximum shear load which rivet assembly can withstand. A deflection of 0.40 mm was allowed around lining under the rivet head within which the lining is in the linear limit. Beyond 0.40 mm, it behaves non-linearly leading to the fracture point.

On comparison of flat head rivets, taper head rivets are showing minimal deformation of lining under the rivet head for the same setting load. For the same dimensions the area of contact for a taper head river is 4.50 % more than a flat head rivet because of its tapered geometry. The rivets are designed to resist the surface pull on the riveting assembly during the application of brake. The cross-sectional area resisting this surface pull was found to be 27 % more for a tapered head rivet over a flat head rivet. Because of higher contact area, the stresses are distributed to wider area resulting in lesser stress formation and deflection in tapered head rivets.

While considering rivet materials, brass is having higher tensile strength (550 N/mm^2) and Poisson's ratio (0.35) than steel. Because of its higher Poisson's ratio in elastic limit, the lateral displacement / radial displacement will be more. From the finite element analysis, as mentioned in Stage 4, it was found that the radial deflection of brass is higher than steel for the same load. The need for considering higher radial displacement at this juncture is to eliminate the clearance between rivet shank and rivet hole.

For better performance, as it was mentioned earlier the attachment of lining and rivet should form the close fit. It was observed from finite element study also that the displacement was more for brass rivet compared to steel rivet. A typical calculation will show that for a particular condition (dimensions and longitudinal deflections are same), the steel circular cross section will get a deformation of 0.22 mm and brass material as 0.26 mm. From the finite element studies, the setting force is limited between 1500 KGS to 1750 KGS considering deformation. For the flat rivets of same dimensions, it is limited well below 1500 KGS. But in the case of steel rivets, the setting force is safely transmitted to the lining up to 2000 KGS setting force.

Some features are identified while comparing all the deflection contours and stresses. More diffuse deformation of structure was found out in the lining counter bore in tapered rivet head model. The region near the base of the counter bore is having higher deflection because of sudden change of geometry and development of high stresses.

During the riveting, the region under the rivet head is in compression and the remaining lining material which is unloaded is under tension. Material will fail if it has a lesser tensile strength in the normal direction and exceeded by the tensile stresses induced above the rivet head during riveting. This will cause a problem of rivet chipping. The greater deflection in the normal direction was observed because of lower elastic modulus in the vertical direction.

From the experimental studies, it was found that at the excessive loading conditions, a ring crack was developed at the base of counter bore since the lining locally fractures in tension. Figure 3 shows the finite element mesh of a heavy-duty brake liner bonded with the shoe. Figure 4 and Figure 5 illustrate the finite element mesh of a flat head rivet and the finite element network of the block under the rivet head respectively. Figure 6 gives the deflection contour of a lining under dragging forces.

The drag force which is causing a surface pull in the lining was calculated for this application and the load conditions were applied in the cross-sectional area of the crimp height of the model. The lining was modeled with 2.20 mm, 3.33 mm, 3.80 mm, 4.00 mm, and 4.30 mm crimp heights and the stress and deflection contours were obtained for all models. For the crimp height of 2.20 mm, the safety factor of the lining was just 1.0 in the static condition, and it can be reduced further in the dynamic conditions. The crimp height versus safety factor graph is shown in Figure 7. By considering the loss in volume of the wearable lining in addition to the safety factor, the optimum crimp height was decided.

The finite element model used for this analysis considered only the compression elastic modulus. The composite material behavior was studied, and the theoretical results were correlated with experimental results to take a decision about the application of finite element analysis tool for the determination of stresses and strains in the composite brake linings material.

CONCLUSIONS

Load deflection characteristics of the non-asbestos brake linings material was studied for better understanding about material behavior of a particular product. The present study shows that the friction material is weaker under tensile loading.

The elastic moduli in the direction along the fiber reinforcement and normal to the fiber reinforcement were determined from the stress-strain graph It was found that the material is having higher compression strength normal to the fiber direction and it's greater than the compression strength along the fiber direction. This phenomenon is attributed to the orthotropy of friction material.
The finite element approach was introduced to evaluate the stresses and deflection contours of the rivetted assembly. The results of the finite element analysis were correlated with experimental setting force and rivet holding strength data.

From the experimental rivet holding studies, it was found that for a taper head rivet, optimum rivet holding strength was exhibited at the setting force of 1600 KGS.

Further analysis shows that the rivet holding strength of brass rivet is not varying much with different setting force in the optimum range and steel rivet exhibited significant variations. Therefore, inaccurate riveting of steel rivets will negatively affect the braking performance. Because of the higher radial deformation comparing the normal deformation and the wider range of maximum rivet holding strength, brass rivet is recommended for heavy duty brake linings.

From the finite element analysis, it was found that for the crimp height of 2.20 mm, the lining safety factor is less than 1.0 in dynamic conditions and the chances of failure will be predominant. Therefore, there is a need to increase the crimp height to prevent the failure of the lined shoes in dynamic brake applications. The optimum crimp height was designed by considering the loss in wearable volume of the lining in addition to the safety factor of lining.

A tapered head rivet is recommended due to greater area of contact for the same dimensions and lesser tensile stresses induced in the unloaded brake lining at the riveted condition.

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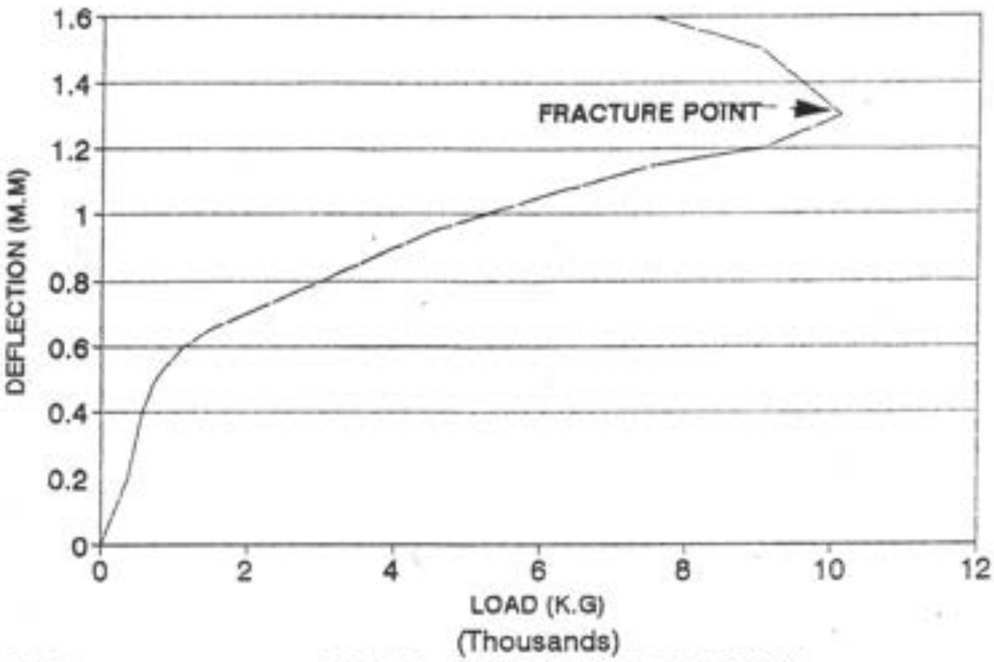

PRODUCT: HEAVY DUTY BRAKE LINER

FIGURE 1. LOAD DEFLECTION GRAPH (UNDER TRANSVERSE COMPRESSION LOADING)

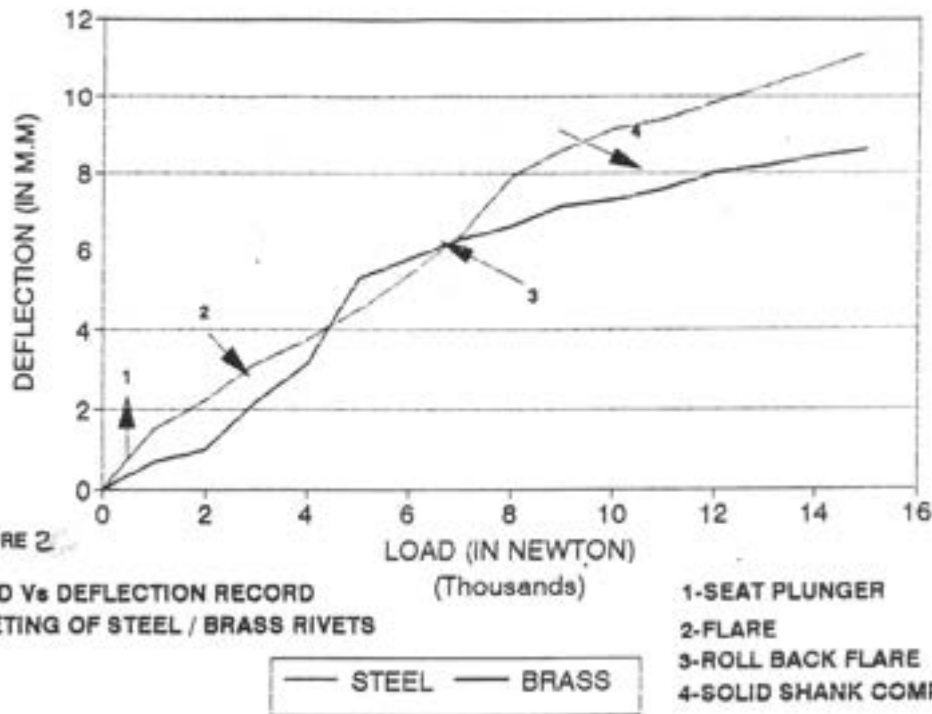

FIGURE 2

LOAD Vs DEFLECTION RECORD
RIVETING OF STEEL / BRASS RIVETS

1-SEAT PLUNGER
2-FLARE
3-ROLL BACK FLARE
4-SOLID SHANK COMP'N

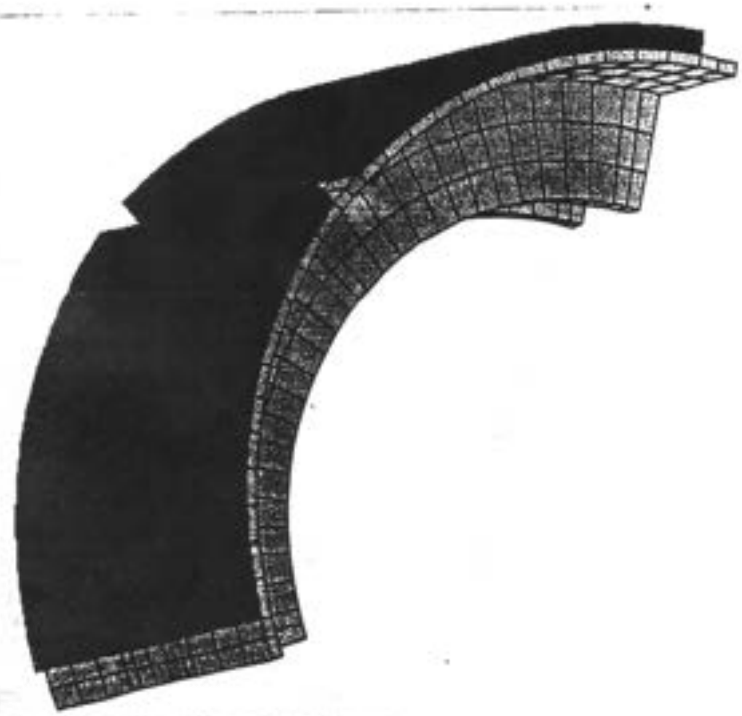

Figure 3. Finite Element mesh of a heavy duty taper brake liner bonded on a shoe

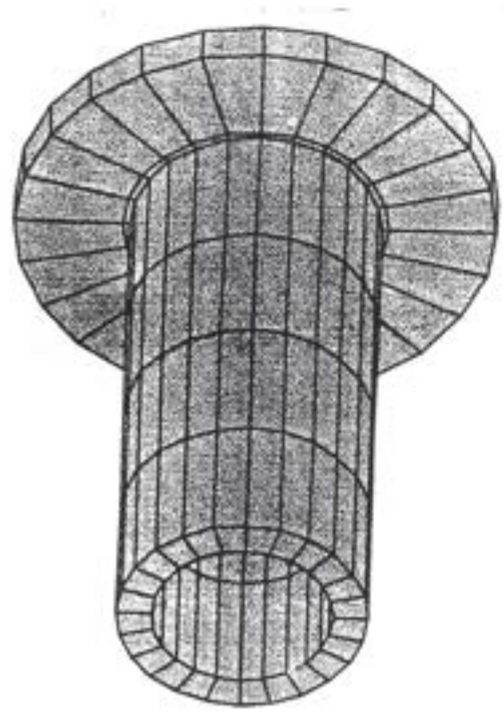

Figure 4 Finite Element model of a flat head rivet

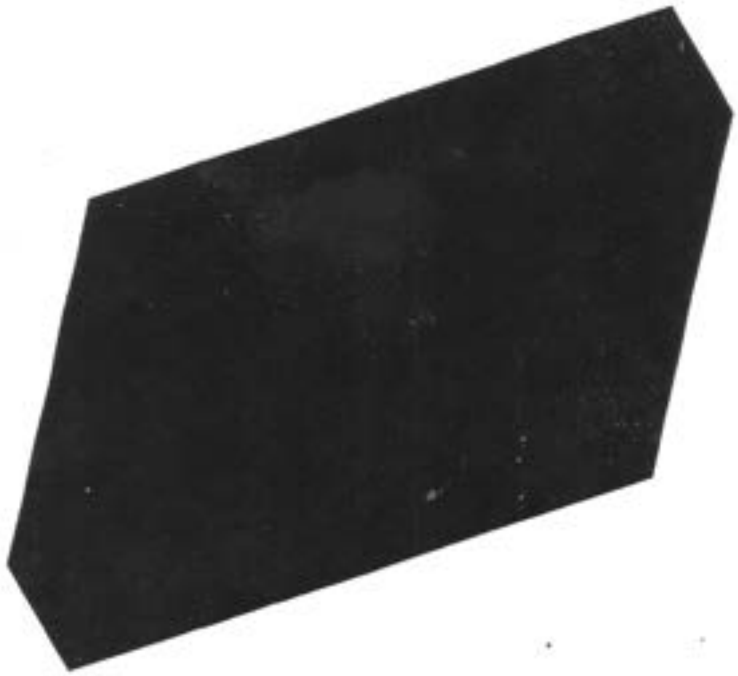

Figure 5. Finite Element network of the lining under taper head rivet

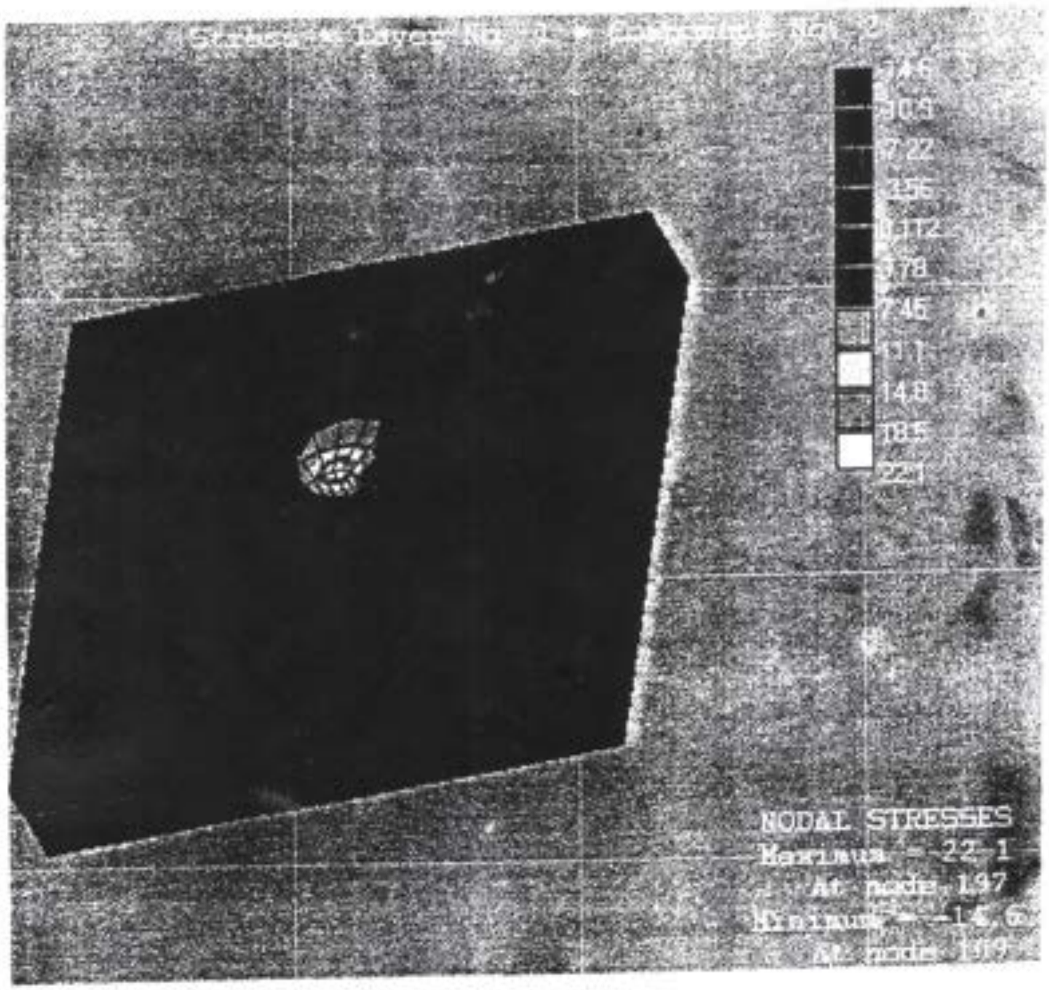

Figure 6.
Stress Contour of brake lining rivet hole under drag forces

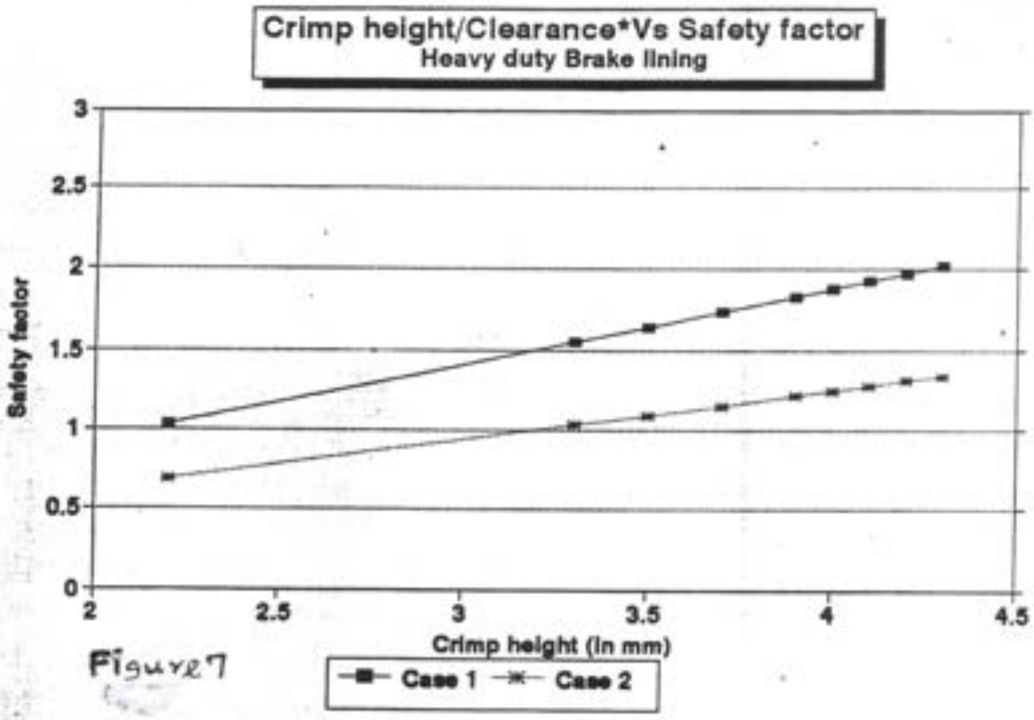

Figure 7

* Clearance between lining and rivet shank

Case 1. No clearance between lining rivet hole and rivet shank at the bulged condition
Assumed the rivet hole diameter as 6.70 mm Avg. (6.55/6.83 mm) and bulging of brass rivet as 6.70 mm

Case 2. Clearance = 0.1 mm between lining rivet hole and rivet shank at the bulged condition
Assumed the rivet hole diameter as 6.90 mm Avg. (6.72/7.04 mm) and bulging of brass rivet as 6.70 mm