COMPUTER AIDED ANALYSIS AND DESIGN OF BOOTS FOR AN ORTHOPAEDIC USAGE

A MASTER'S THESIS

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Mechanical Engineering
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By
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ABSTRACT

COMPUTER AIDED ANALYSIS AND DESIGN OF BOOT FOR AN ORTHOPAEDIC USAGE

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In this study, a soldier boot has been modelled and analysed using ANSYS Finite Element Program. The constructed model has been improved using multi-layered sole for various materials to allow any further development. The optimisation process is applied to sole thickness based on the preliminary solution under the human weight. The minimisation of volume or strain energy of sole subjected to stress constraints is carried out for optimisation. The upper part of the boot is not considered in analysis.

Key words: Finite Element Method, ANSYS, Computer Aided Analysis (CAA), Boot, Optimal Design.

ÖZET

ORTOPEDİK KULLANIM İÇİN BİLGİSAYAR DESTEKLİ
BOT ANALİZİ VE TASARIMI

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Bu tezde, asker botunun modeli ve analizi ANSYS Sonlu Elemanlar paket programı ile gerçekleştirilmiştir. İleriye yönelik bir çalışma yapılabilmesi için birden fazla katman kullanılmış ve farklı malzemeler için model geliştirilmiştir. İnsan ağırlığına göre ilk çözümler elde edilmiş ve bu çözümlere dayanarak taban kalınlığının optimizasyonu gerçekleştirilmiştir. Optimizasyon için taban hacminin azaltılması veya sistemin strain enerjisinin düşürülmesi ele alınmıştır. Bot analizinde, botun üst kısmı ele alınmamıştır.

Anahtar Kelimeler: Sonlu Elemanlar Metodu, ANSYS, Bilgisayar Destekli Tasarım, Bot, Optimum Tasarım.

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CHAPTER I

INTRODUCTION

Boots are designed to prevent soft tissue and skeletal damage to the feet under heavy usage. It should offer customers the flexibility, comfort, shock absorption to operate in any type of terrain, while providing them with protection against many kinds of weather conditions. Another expected feature is the weight of the boot. The weight and other features should be optimised without compromising which from the performance of boot.

All kinds of boots generally have two parts. While the outer shell comprised of a leather like material due to fashion, sole base is required to be wear resistant, flexibility, waterproof and energy returning material. Sole base can be single layer or multi-layer depending on requirements.

The analysis and design of boot is quite a complex process. The comfort and strength must be satisfied together. Selection of material, shape and strength of sole should be considered during modelling, analysis, and optimisation. In this study an ordinary soldier boot has been considered for the analysis and optimisation and the geometric coordinates of the boot are taken from a sample boot for the modelling purpose. The model has been constructed using ANSYS 5.3 Finite Element program based upon the coordinates of real boot. The upper part of boot has been modelled as shell. The sole base is considered as 3D geometry and modelled by three layers with different thicknesses and materials.

The material properties used for the modelling are obtained from material handbook [1] and the mechanical properties of materials obtained from shoe manufacturers. The loading of the boot depends on the anatomy of feet and body. The weight of the body is not linearly distributed over the sole. The sole is assumed under static loading of a 70 kg person and the load is distributed on the sole into three regions. These regions are the centre of heel, midfoot and forefoot.

The analysis and design of boot has been carried out using ANSYS 5.3 Finite Element package. The analysis considered in this work that involves the linear elastic stress and contact analysis of sole. A series of runs have been undertaken to reach optimal sole thickness.

CHAPTER II

LITERATURE SURVEY

2.1 INTRODUCTION

The pressure under foot is measured to obtain the affects to the foot and leg. It is used to determine the shock absorption characteristic of shoe soles, especially in athletic shoes. Besides, forces on the sole is calculated to find friction characteristic of shoe soles. Computer aided design (CAD)/Computer aided manufacturing (CAM) systems are used to make personally orthopaedic shoe, because all human footprints differ from each other.

In literature many works have been carried on shoes, their design, and some studies on pressure measurement between foot and shoe, and friction characteristics of shoe soles. These aspects have been reviewed in the following sections. The pressure measurement between foot and shoe is given in Section 2.2. Furthermore friction characteristics of shoe soles is reviewed in Section 2.3. In Section 2.4 literature on modelling and design are presented. Furthermore, some industrial visits are mentioned in Section 2.5. Finally, the conclusions of literature survey have been discussed in Section 2.6.

2.2 PRESSURE MEASUREMENT

In the literature there are two common methods to measure pressure distribution under foot during walking. One of them is to use a force plate system and the other method is applied by placing sensors in the insole of a shoe.

A force-sensitive pressure sensor as Umbilical Data Acquisition System is developed by Zhu et. al.[2]. According to this system, force-sensitive pressure sensors, which are located under the centre of the heel, the five metatarsal heads, and the big toe of each insole of shoes, are used to measure pressure under foot during walking or standing on.

Another method, in which pressure sensors are used, is F-Scan Gait Analysis system. In this system, pressure sensitive insole is required and square cells are constructed by sandwiching printed circuit of force-sensitive resistive material in Mylar film. Similarly foot pressure is measured by Lord and Hosein [3] during walking into three regions which are forefoot, midfoot, and hindfoot. According to measurements, the largest peak of pressure occurred under metatarsal heads in the forefoot.

In force plate system, an aluminium top plate is supported on each corner by cantilever blocks machined from aluminium. The top plate rests on rounded aluminium supports, which are screwed to the cantilever blocks. Strain gages are attached on top and bottom of the cantilever. Force platform, which is easily constructed to measure vertical dynamic force associated with jumping and running activities, is designed by Calder and Smith [4]. Also, force plate system is used by Dickenson et. al.[5] to measure the shock waves occurring on heel during running without footwear.

Force platform used by Nigg et. al.[6] to investigate the influence of midsole hardness and running velocity on impact forces in foot. Due to the study, impact peak forces are measured at different speeds and different midsole hardness.

Biomechanical analysis of foot is investigated by Nicol and Paul [7]. In this analysis, forces on foot are calculated using pressure distribution under foot during walking where pressure distribution is taken from literature. As a result, It has been concluded that the muscles of the leg absorb affects of forces.

The compressive properties of the heel pad is studied by DeClercq et. al.[8], during the heel strike when running (barefoot and shoe). Force platform, which is named as Kistler force platform, is used to measure vertical ground reaction forces.

In the literature, pressure distribution under the foot is measured not only during walking but also during standing on the ground. Pressure distribution of the foot based on the Moire Shadow technique is measured by Fok [9]. According to this technique, a large number of individual pressure transducers are arranged in a matrix over the surface. And by mirroring the point light source the pressure distribution is taken with camera.

According to the literature the shock absorption characteristics of shoe sole is important for human health. For measuring shock absorption characteristic, Shock Attenuating Characteristics of Material test is made for athletic footwear by Ireland [10]. In this test shock attenuating characteristics and rapid rate force-displacement relationships of the material systems, which are used insole, midsole and outsole of the athletic footwear are measured.

2.3 FRICTION CHARACTERISTICS OF SHOE SOLES

In literature many works have been done about friction characteristics of shoe soles. Because of the friction, the slip tendency of shoe may decrease on the ground. So friction characteristics of shoe sole are an important parameter for the design purpose.

Horizontal Slipmeter is used by Irvine [11] to test the slip resistance of shoe and floor materials. The sole materials are tested in two conditions, wet and dry, on two floor surfaces, vinyl asbestos and terazzo. Furthermore slip resistance of shoe sole is inspected by Buczek and Barks [12] during walking. But, force platform is used to measure applied foot forces. From the net force, forces are divided into two parts as a shear and normal force. The shear force is equal to slip resistance. Then, according to slip resistance, friction constant of surface is calculated. As a result of this calculations typically friction constant is 0.4 for prediction of slip. A Similar work is done by Fendley and Marpet [13]. In this work, as before friction characteristic of shoe sole and floor is measured and same as before, force plate is used to measure applied force.

2.4 MODELLING AND DESIGN

A program, which has been developed by the Department of Computer Science at North Carolina State University, is used by McAllister et. al. [14]. The program is an interactive computer graphics program that is developed for the modelling of shoe lasts from digitised images of feet or digitised images of commercial shoe lasts. The program contains operations for region addition and deletion, techniques for narrowing the ankle area, methods for toe extension, operations to allow shoe inserts. Shoe last is modelled with an error tolerance. Coon's patches of shoe last are obtained by data reduction program. Then, these patches are transmitted to a milling machine for machining the last. A similar work has been done by Lord et. al.[15]. Firstly shoe last data's are transferred to the computer as a wire frame by hand. Then, the orthopaedic shoe upper design is made with the aid of computer for different styles and patterns.

An integrated CAD/CAM system is made by Bao et. al.[16] to digitise the foot, a graphics sub-system is used to create the geometry of the last from the foot model, and the tool cutter paths are generated for a numerical control machine to cut the shoe last. To generate the tool cutter path, firstly, foot is scanned for orthopaedic shoe and making foot shape modifications, the shoe profile is then obtained.

The program, run under I-DEAS package program, is developed by Enöz [17] to analyse and design of the sport shoe soles under different boundary and loading conditions. Designed shoe sole is analysed with finite element program to obtain stress, strain and displacement values.

2.5 INDUSTRIAL VISITS

During this study, some shoe manufacturing companies were visited in order to obtain some sole materials and knowledge about boot. Major aim of the visit is to learn manufacturing process and criteria used in the design process.

The first visit was done to OPAK Shoe Company [18], which is one of the largest shoemakers in Gaziantep. Their main products are slipper, shoe and boot. Natural rubber and polyurethane sole material is obtained from OPAK Shoe Company.

The second visit was done to Yesil Kundura Shoe Company [19], which is the main manufacturer of boot in Turkey. Some sole materials obtained from Yesil Kundura. During the visit, the production steps of the boot were examined. The steps are;

- Preparing the dough of rubber with raw materials and chemical components,
- Mixing of the dough until the specified density is obtained,
- Rolling of the dough in order to obtain uniform material and to get the thin rubber plates,
- Cutting of the rubber plate to the shoe sizes,
- Putting the cut rubber parts into the shoe dies,
- Hot pressing or injection of the soles,
- Putting out the cooled sole from the dies and finishing,
- Sticking the sole with the upper side of the boot which is prepared separately from the sole,
- Cleaning of the boot,
- Quality control of the produced boot.

In addition to those some additional shoe materials were obtained from Danner Shoe Company in USA. Tension tests of the sole materials were made on INSTRON Tension Test Machine and the results are used in analysis of the sole behaviour under load.

2.6 CONCLUSION ON LITERATURE REVIEW

The results of the literature survey can be summarised as follows:

- In spite of many studies on shoe design for making orthopaedic, there is no work on boot analysis and optimisation.
- Lack of availability of material properties, proper geometry definition of foot and adequate analysis program during the design process.

- In the contact analysis, friction coefficient is taken as 0.4, which is given in literature.
- The load on the sole is generally distributed in three regions, which are heel, five metatarsal head and great toe. In the following course of work, these load distribution is adapted to analysis.
- As far as the author knowledge there is no study on contact analysis of shoe.

The main objective of this thesis is the analysis and optimal design of shoe soles. The specific objectives are summarised as:

- to study modelling of boot using B-Splines and Non-Uniform Rational B-Splines (NURBS)
- to integrate the geometric modelling , contact analysis and optimisation process
- to obtain the correct material type.
- To obtain the optimal thickness based on volume minimisation for the boot sole.

CHAPTER III

FINITE ELEMENT METHOD

3.1 INTRODUCTION

In this chapter a brief introduction to Finite Element Method (FEM) and ANSYS analysis package is presented. Finite element analysis and their applications are explained in Section 3.2. The applications of ANSYS Finite Element package program are discussed in Section 3.3. Contact phenomenon, contact non-linearities, ANSYS contact elements and contact stiffness are explained in Section 3.4. Finally design optimisation module of ANSYS is summarised in Section 3.5.

3.2 FINITE ELEMENT METHOD

Finite element method is a numerical analysis technique, which is used for obtaining approximate solution to a wide variety of engineering problems, and it has become a useful tool in CAD. FEM has been extensively used in the field of structural mechanics. It has also been successfully applied for the solution of many types of engineering problems such as heat conduction, fluid dynamics, electric and magnetic fields. In more and more engineering problems today we find that it is more economical to obtain approximate numerical solutions rather than exact-closed form solutions.

FEM basically consists of pointwise discretisation for the satisfaction of boundary conditions in terms of nodal values and interpolation of shape function and piecewise discretisation to simplify the assumed trial solution. There are few different formulations for finite elements. The finite element can be formulated based on the assumed displacement field and the principle of minimisation of potential energy. Detailed treatment of the standard finite element formulation can be found in many textbooks, for example in Bathe [20]. In the following sections, however only the fundamental module of ANSYS package program used by subsequent parts of the present work are outlined.

The analysis of boot, which is presented in this thesis, is done based upon the finite element method. FEM is used as a tool for the determination of the deformation and pressure distribution in the sole at the contact surface between boot and ground.

3.3 ANSYS FINITE ELEMENT PACKAGE PROGRAM

3.3.1 General Information

ANSYS [21-26] is a large scale, general purpose, finite element program used by design engineers for structural, thermal, fluid, electrical and static electromagnetic analysis. ANSYS has been used since 1970 in many industries, including nuclear, aerospace, automotive, power, transportation, bio-mechanics, steel, railroad, packaging, civil construction, and electrical-electronics industries.

3.3.2 Program Capability

ANSYS is one of FEM based package program. ANSYS has various modals such as structural, thermal, fluid, impact. It can analyse linear or non-linear cases in two or three dimensions. ANSYS includes submodelling for detailed regions of linear and non-linear structures. ANSYS has three main phases of finite element analysis; pre-processing, solution and post-processing

3.3.3 User Interface and Modelling Capability

ANSYS allows users to create their own models using the pre-processing. Both mesh and loads can be generated using automatic procedures. On-line documentation [24] is available for each command. ANSYS post-processing supports many graphic options-hidden line, section, x-y plots, distorted shape, and contour maps of stresses or temperatures. ANSYS post-processing also includes a data base language so that results can be selectively examined.

The ability to pass information between various types of design and analysis programs adds flexibility to computer aided engineering analyses. Specifically, there is a need to precisely transfer geometry data from CAD packages to analysis and manufacturing. ANSYS interfaces with many CAD systems by supporting open systems. ANSYS recognises that NURBS mathematics is emerging as an industry standard for geometry data. Therefore, geometry data from CAD packages based on NURBS-based representation can be transferred precisely to the ANSYS program, without any inherent loss of accuracy. ANSYS also supports the Initial Graphics Exchange Specification (IGES) as the industry standard by working closely with CAD vendors to ensure the technologies are an effective tool for transferring data. IGES includes support for complex trimmed surfaces, up to and including the NURBS representation.

The ANSYS program uses a single, centralised database for storage of all model data and solution results as shown in Figure 3.1. Model data are written to the database using the ANSYS pre-processor. The solution uses the informations in the database. Post-processing result data is accomplished using the post-processors, which can access the data directly from the database.

The ANSYS element library consists of over 100 element types. Many have options, which allow further specialisation of the element formulation in some manner, effectively increasing the size of the element library. Elements are categorised as two-dimensional or three-dimensional and may take the form of a point, line, area, or volume. Both linear and quadratic elements are available. Most elements allow appropriate element loading such as pressure, temperature, convection, etc.

In University of Gaziantep, ANSYS 5.4 is currently in use but ANSYS 5.3 is used in this thesis. Due to this, the date of figures is in 1997.

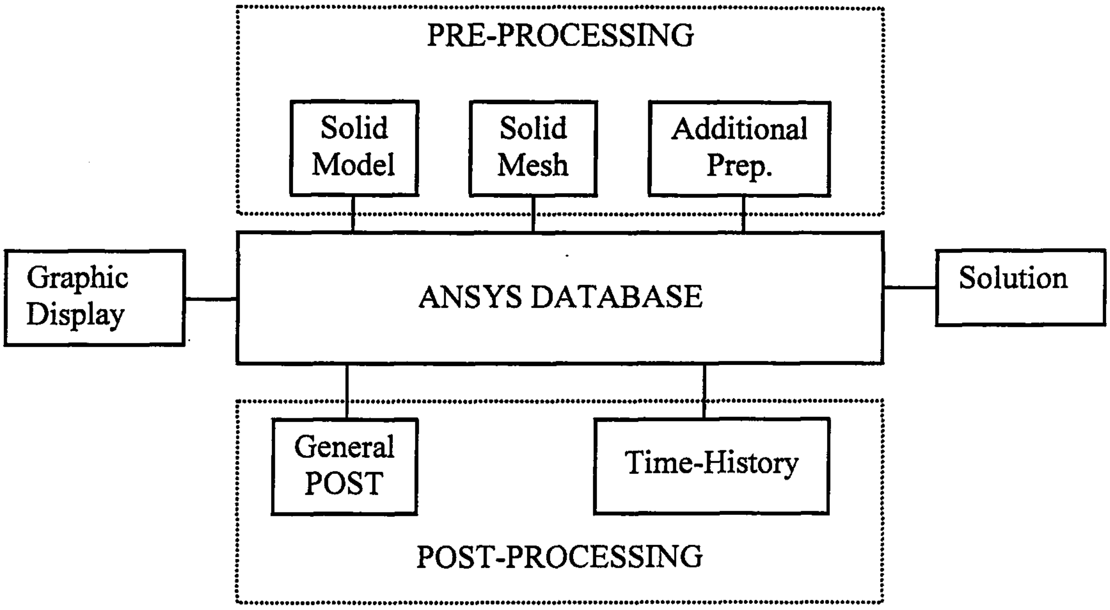


Figure 3.1 ANSYS Centralised Database.

3.4 CONTACT PHENOMENON

Contact is a phenomenon that occurs in most engineering applications: joints (bolted or sliding), metal forming, rolling operations, dynamic pipe whip, crash dynamics, assemblies of components, interference fit, etc. A wide area of engineering problems may be solved with the ANSYS Finite Element program. Researchers are interested in stresses, deflections, deformations, and forces that occur due to the contact between structural parts. General contact is treated as a boundary non-linearity. In the ANSYS [23] non-linear contact elements, analysis of surface-to-surface contact with large deformations, contact and separation, and sliding with friction are possible.

3.4.1 Contact Non-linearities

Contact non-linearities occur when two or more components (or parts of one component) come into contact with each other (or itself) during the course of the deformation process. Contact non-linearities also occur when two components slide relative to one another. Contact is a non-linearity because of the changing boundary conditions and forces at contact area.

General contact is represented by following the positions of points on one surface (the contact surface) relative to the points or lines or areas of another surface (the target surface).

To use the contact capability, the areas where contact might occur during the deformation must be identified. This identification is done through elements, which will then track the kinematics of deformation process. There are two basic element types that may be used in analysis and they identify the type of contact conditions [23]. These are node-to-node contact and general surface-to-surface contact

Node-to-node contact occurs whenever a single point will come into contact with another point. The exact location of contact is presumed to be known beforehand. Only small amounts of relative sliding deformation are allowed.

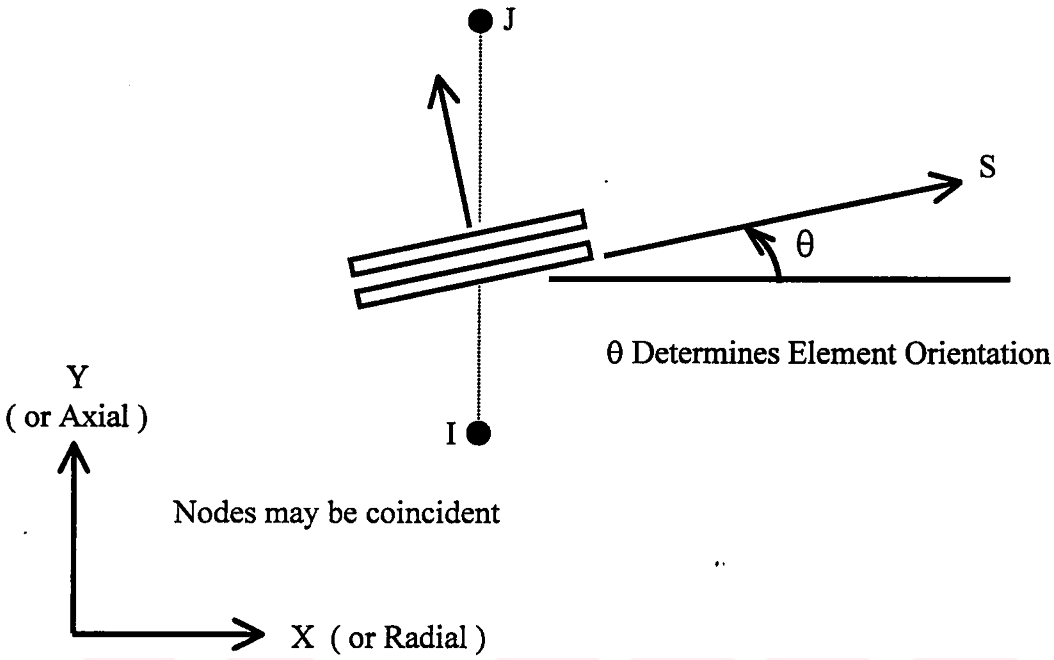
Surface-to-surface contact occurs when two surfaces may come into contact. The exact location of the contacting area may not be known beforehand. Large amounts of relative sliding are permitted. Also the opposing meshes do not have to have the same discretisation. The two surfaces may both be part of a deformable body or one may be a rigid surface.

3.4.2 Contact Elements

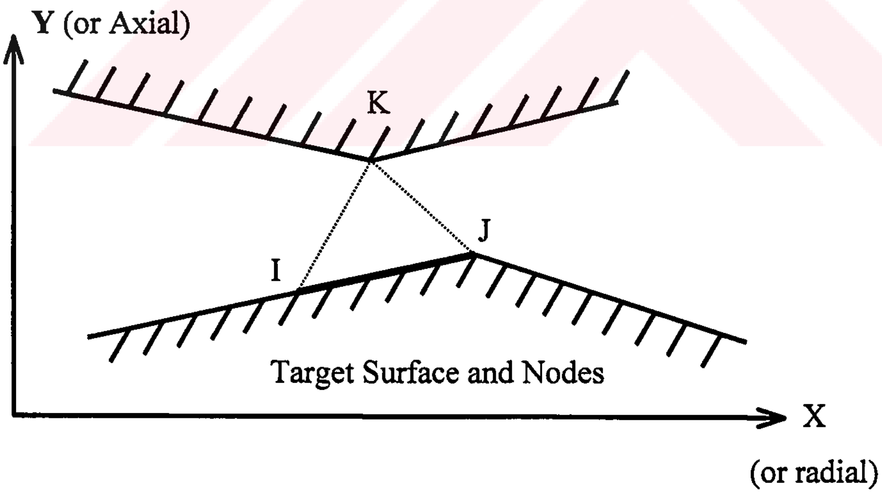
The contact elements are used to track the relative positions of the two surfaces. In two dimensions the node-to-node contact element, CONTAC12, and the node to surface contact element, CONTAC48 (planar and axisymmetric) are shown in Figure 3.2 (a) and (b) [23]. In three dimensions the node-to-node contact element is CONTAC52, and the node to surface contact element is CONTAC49, and they are shown in Figure 3.3 (a) and (b) [23] respectively. These contact elements are finite elements that apply appropriate forces to nodes on two surfaces to account for contact and friction.

3.4.3 Contact Stiffness

In order to handle a contact analysis with the finite element method, a stiffness relationship must be established between the two contact areas when contact occurs.

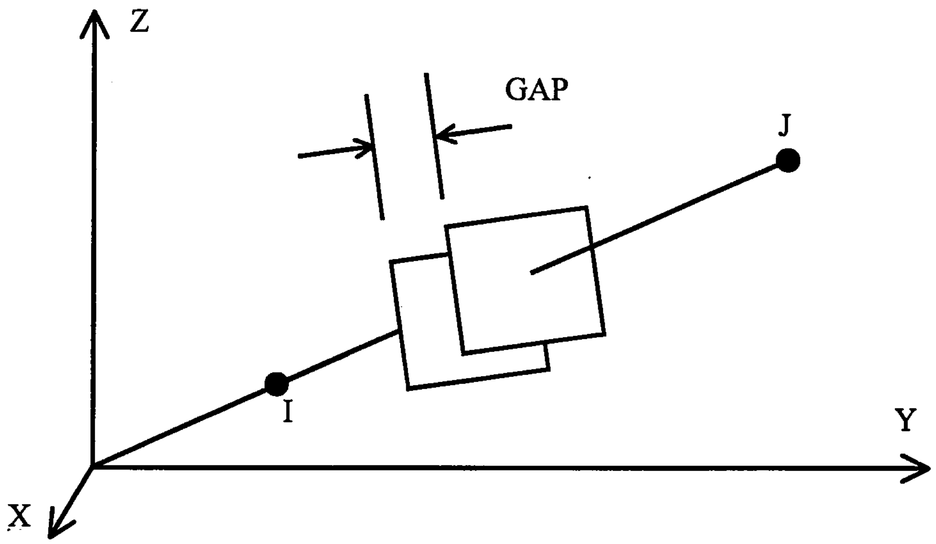


(a) CONTAC12

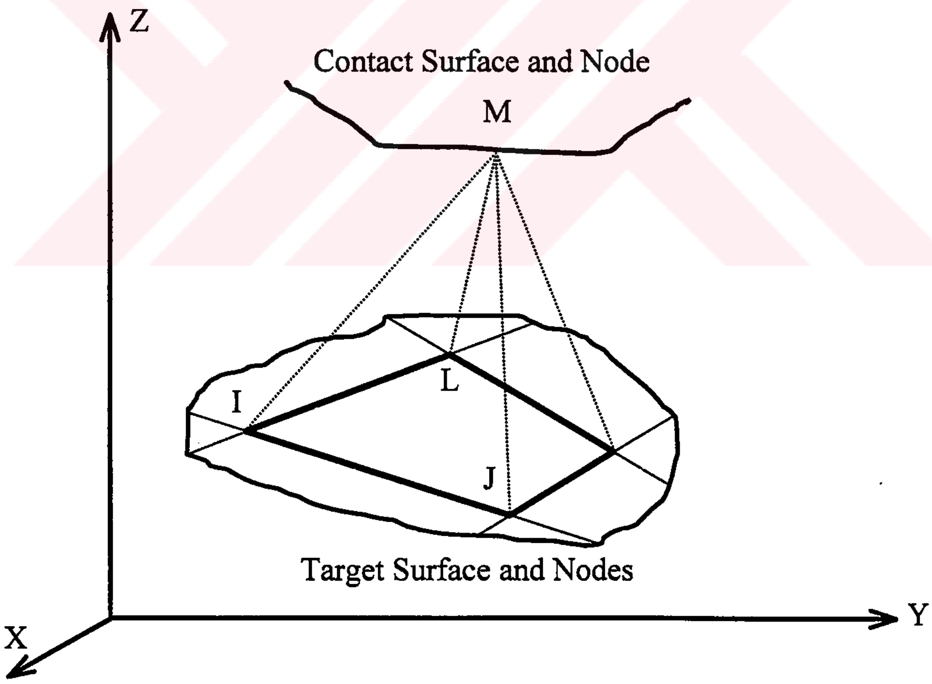


(b) CONTAC48

Figure 3.2 Two and Three Dimensional Point to Point Contact Elements [23]



(a) CONTAC52



(b) CONTAC49

Figure 3.3 Two and three Dimensional Point to Surface Contact Elements [23]

Otherwise, the two areas will penetrate each other. This relationship is established through a spring that is put between the two contacting areas when contact occurs. The spring will deflect an amount λ such that equilibrium is satisfied [25],

$$F = k_n \lambda \tag{3.1}$$

where k_n is the spring stiffness in this equation and it is called the contact stiffness and has the unit of force/length.

The amount of penetration, or incompatibility, between the two surfaces is therefore dependent on the stiffness k_n. Ideally there should be no penetration, but this implies $k_n = \infty$. High values of k_n also leads to ill conditioning of the global stiffness matrix, as well as convergence difficulties. Practically, a high enough stiffness value is required that the contact penetration is acceptably small, but low enough that the convergence or ill conditioning problems will not occur.

The value of k_n that should be used depends on the relative stiffness of the areas in contact. This stiffness may be estimated or computed from the local compliance of the components. Stiffness may be estimated using [25]

$$k_n = fEh_l \tag{3.2}$$

where f is a factor between 1 and 100, E is the elastic modulus of contacting material, and h_l is a measure of the characteristic contact length.

For contact between two different materials, the smaller elastic modulus of the two must be used. The contact length h_l depends on the geometry:

- For 3-D, h_l is a typical length associated with the contact area of a single contact point.
- For 2-D plain strain, 1.0 for h_l can be used.
- For 2-D plain stress, the thickness for h_l can be used.

3.5 DESIGN OPTIMISATION

The optimisation module is an integral part of the ANSYS program that can be employed to determine the optimum design. This optimum design is done to satisfy some predefined requirements. According to the design requirements, weight, geometry, stress, energy or temperature may be extrimised for the optimum design. In many situations minimisation of a single function may not be sufficient, so more than one function are used for optimisation. Actually, any ANSYS item that can be expressed in terms of parameters can be subjected to design optimisation.

While working towards an optimum design, the ANSYS optimisation routines employ three types of variables that characterise the design process: *design variables*, *state variables*, and *objective function*. These variables are represented by scalar parameters in ANSYS Parametric Design Language (APDL). The use of APDL is an essential step in the optimisation process.

The independent variables in an optimisation analysis are the design variables [24]. The vector of design variables is indicated by:

$$x = [x_1 x_2 x_3 .....x_n] \tag{3.3}$$

Design variables are subjected to *n* constraints with upper and lower limits, that is,

$$\underline{x}_i \le x_i \le \overline{x_i} \qquad (i = 1,2,3,....,n) \tag{3.4}$$

where n is the number of design variables.

The design variable constraints are often referred to as side constraints and define what is commonly called feasible design space. Now, minimise

$$f = f(x) \tag{3.5}$$

subject to

$$g_i(x) \le \overline{g_i} \qquad (i = 1,2,3,....,m_1) \tag{3.6}$$

$$\underline{h}_i \leq h_i(x) \qquad (i = 1,2,3,....,m_2) \qquad (3.7)$$

$$\underline{w}_i \leq w_i(x) \leq w_i \qquad (i = 1,2,3,....,m_3) \qquad (3.8)$$

where f is the objective function, g_i, h_i, m_i are state variables containing the design, with underbars and overbears representing lower and upper bounds respectively, and m_1, m_2, m_3 are number of state variables constraints with various upper and lower limit values

The state variables can also be referred to as dependent variables in that they vary with the vector x of design variables.

Equations (3.5) through (3.8) represent a constrained minimisation problem of which the aim is the minimisation of the objective function f under the constraints imposed by equations (3.4,3.6-3.8)

3.5.1 The Best Design Set

As design sets are generated by methods or tools and if an objective function is defined, the *best* design set [24] is computed and its number is stored. The best set is determined under one of the following conditions.

1 If one or more feasible sets exist the best design set is the feasible one with the lowest objective function value. In other words, it is the set that most closely agrees with the mathematical goals expressed by equations (3.5-3.8).

2 If all design sets are infeasible, the best design set is one closest to being feasible, irrespective of its objective function value.

3.5.2 Optimisation Methods and Design Tools

The ANSYS optimisation procedure [24] offers several methods and tools to address the mathematical problem stated above. ANSYS optimisation methods perform actual minimisation of the objective function of equation (3.5). It will be shown that they transform the constrained problem into unconstrained one that is eventually minimised. Design tools, on the other hand, do not directly perform minimisation. Use of the tools offer alternate means for understanding design space and the behaviour of the dependent variables. Methods and tools that are used in ANSYS optimisation module are [25];

- Single loop analysis tool
- Random tool
- Sweep tool
- Factorial tool
- Gradient tool
- Subproblem approximation method
- First order optimisation method.

But, the ANSYS program offers two optimisation methods to accommodate a wide range of optimisation problems. The *Subproblem approximation method* is an advanced zero-order method that can be efficiently applied to most engineering problems. The first order method is based on design sensitivities and is more suitable for problems that require high accuracy.

For both the subproblem approximation and first order methods, the program performs a series of analysis-evaluation-modification cycles. That is, an analysis of the initial design is performed, the results are evaluated against specified design criteria, and the design is modified as necessary. This process is repeated until all specified criteria are met.

CHAPTER IV

GEOMETRIC MODELLING OF THE BOOT

4.1 INTRODUCTION

In this chapter, boot modelling is investigated in ANSYS finite element package program by considering various design criteria and materials.

4.2 MODELLING OF THE BOOT

Modelling basically include a geometrical shape construction, mesh generation and boundary conditions and loading. These steps are realised in pre-processing. Furthermore geometrical shape construction may be done in another CAD software and can be transferred to ANSYS Pre-Processor Modal.

4.2.1 Steps of Modelling

In the pre-processing step of the analysis, data items used to model the boot sole are defined. There are, defining element types, physical and material properties, build model (by keypoints, lines, areas, and volumes), and finally mesh generation.

The following steps are carried out for modelling and analysis of the boot:

1- Define keypoints:

Keypoint definition is the first step of the solid modelling you can do this by choosing any of the following ways, either using primitives or giving the keypoints and combining them. We have used second way in this project. Keypoint data is taken from real boot and keypoint view of the boot model is shown in Figure 4.1.

2- Line generation:

After the definition of keypoints you should generate lines between two keypoints. The number of lines is given automatically by ANSYS. It gives numbers to lines according to their sequences. Of course there are a lot of commands which a line can be generated by using them. This is done by using B-SPLINE and LINE. Line view of the boot model is shown in Figure 4.2.

3- Area generation:

Next step is the area generation. Areas are generated with lines. The number of areas is given automatically by ANSYS. It gives numbers to areas according to their sequences. Areas are generated according to lines. Area view of the boot model is shown in Figure 4.3.

4- Volume generation:

After the definition of areas, we can generate volumes between areas. The number of volumes is given automatically by ANSYS. It gives numbers to volumes according to their sequences. Volume view of the boot model is shown in Figure 4.4.

5- Mesh Generation:

Before mesh generation, material property of each element must be given. Young module, Poisson ratio, friction characteristics of material for which the analysis is carried out.

The developed boot model has 1200 keypoints, 1653 lines, 1446 areas, 416 volumes, 9106 nodes and 6704 elements and sole model has 642 keypoints, 1443 lines, 1264 areas, 368 volumes, 1371 nodes and 1371 elements.

After the volume generation and given required parameters, you should divide the lines in desired length to make a mapped mesh or directly give an element size. The elements are the small sub-areas of the model for which the stress, strain and displacement analysis are required. Therefore, a model can be divided into a number of elements in order to get better stress, strain and displacement results. However, the increase in the number of elements, also causes to increase in computation time and data. Consequently, an optimum element size has to be selected by considering computation time and approximation of the results. SOLID45 three-dimensional solid element is used for meshing the boot. Meshed view of the boot model is shown in Figure 4.5. SOLID45 has eight nodes and each node has three degrees of freedom: translations in the nodal x, y, and z directions. The node to surface contact element CONTAC49 is a contact element, which has appropriate forces to nodes on two surfaces to account for contact and friction.

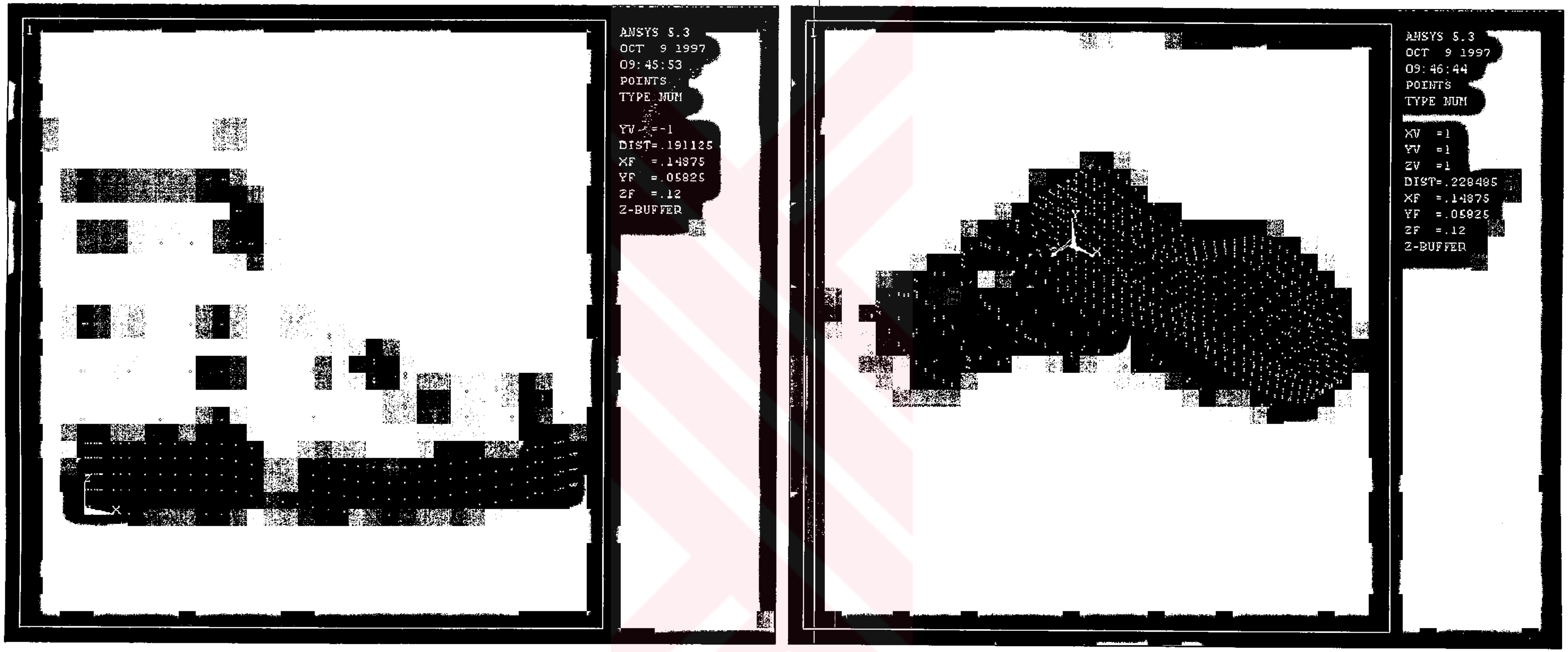


Figure 4.1 Keypoint View of the Boot Model

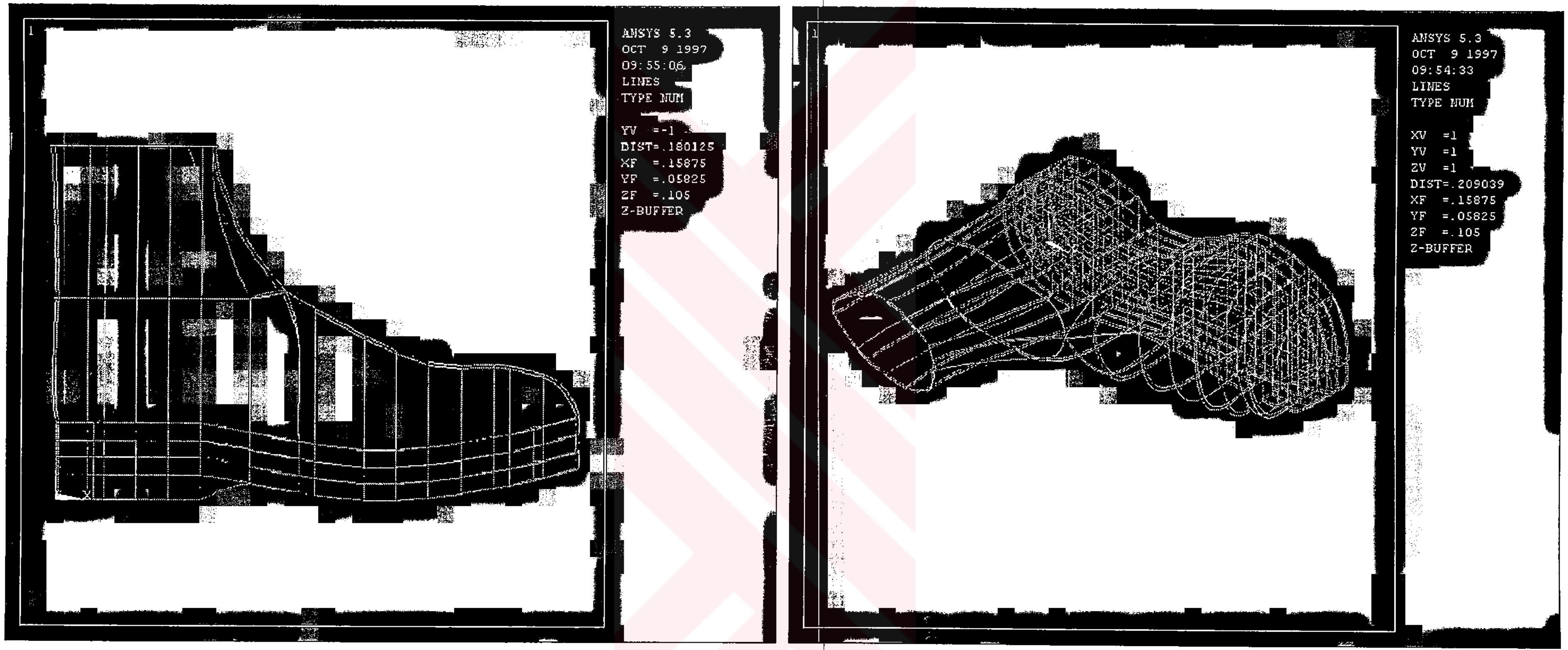


Figure 4.2 Line View of the Boot Model

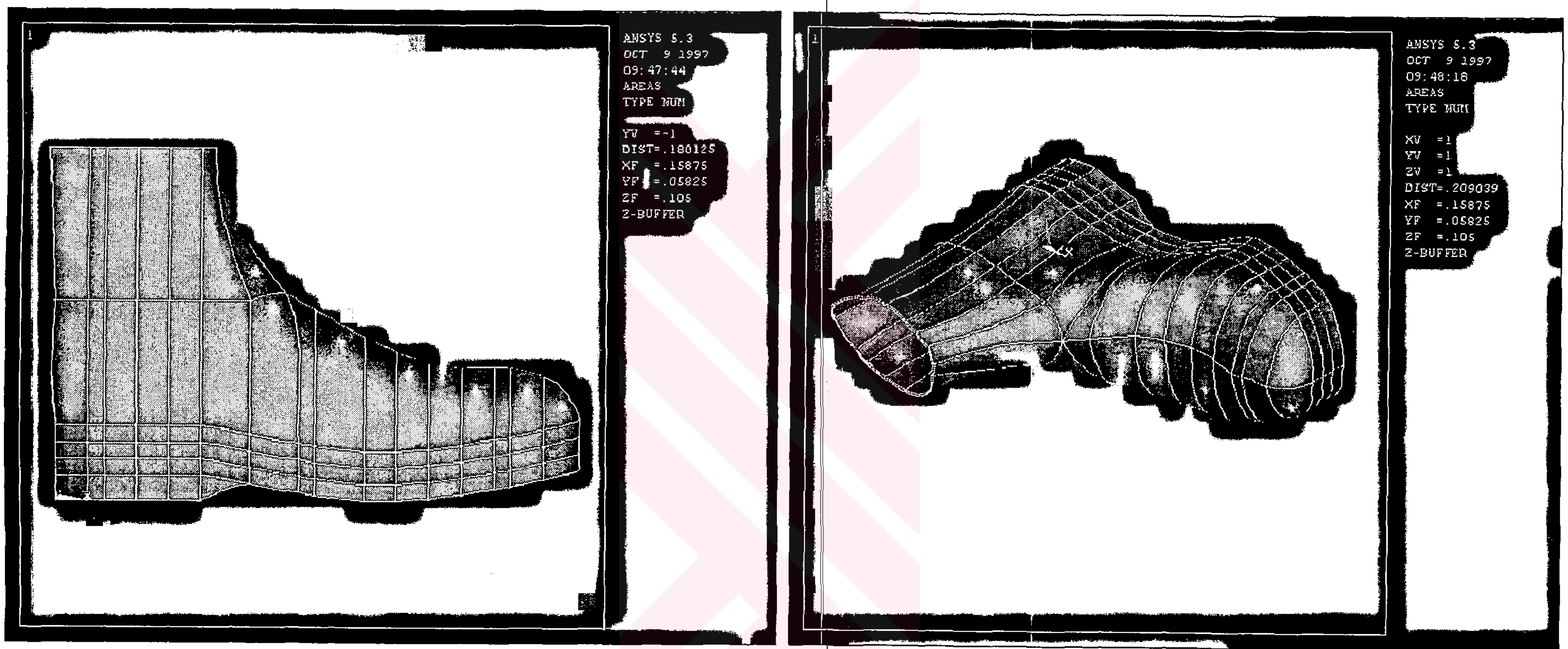


Figure 4.3 Area View of the Boot Model

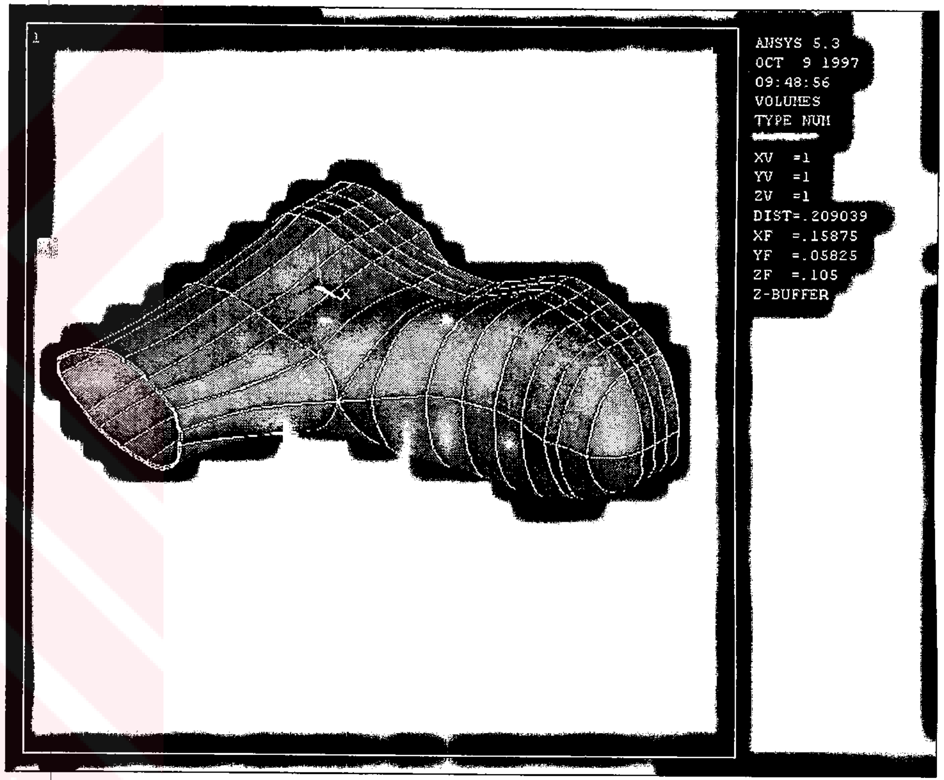


Figure 4.4 Volume View of the Boot Model

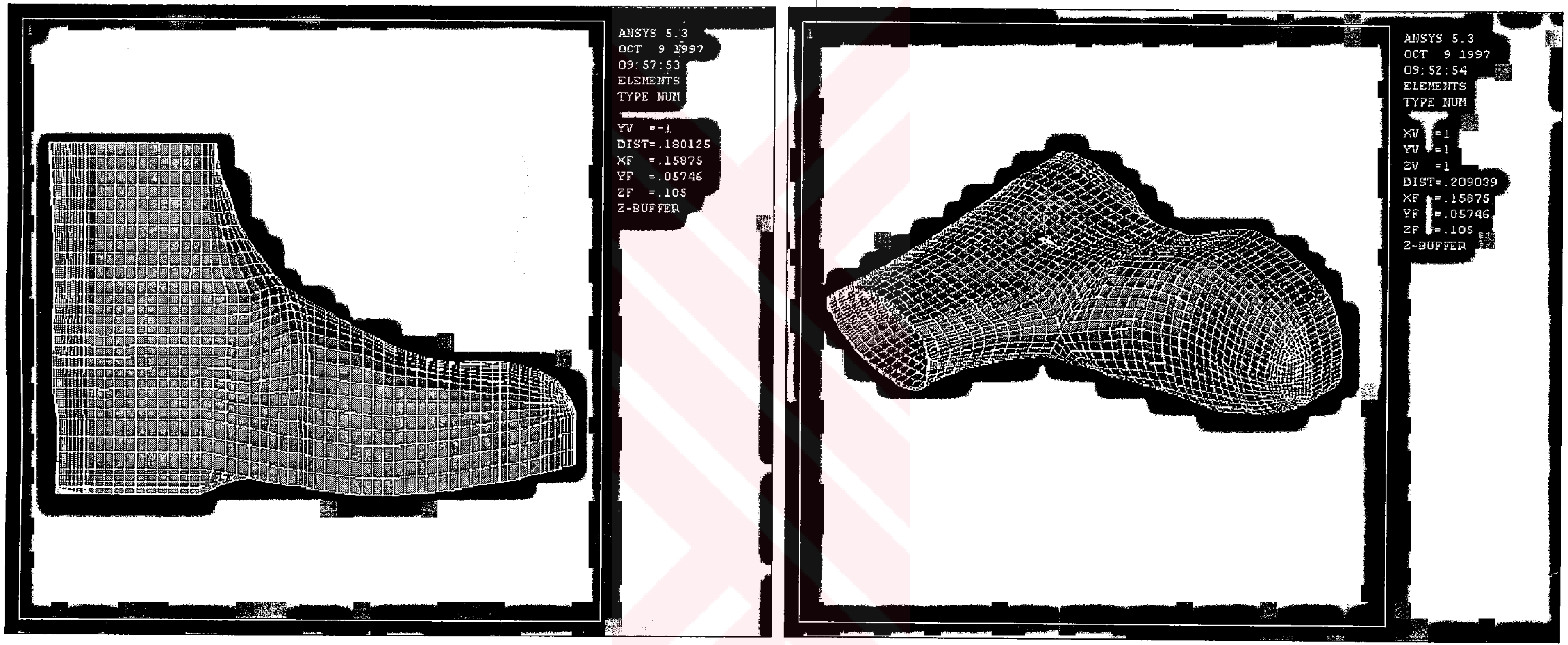


Figure 4.5 Meshed View of the Boot Model

CHAPTER V

ANALYSIS OF THE BOOT

5.1 INTRODUCTION

The analysis and design of boot is quite complex process. First of all it is required to select a suitable material due to usage. The shape of boot is also important due to fashion and function. Lastly the shape of sole is critical for the comfort and health of foot due to orthopaedic need. In this chapter boot sole is analysed with different type of materials. Design criteria in which analysing type is explained in Section 5.2. According to design criteria, analysis and optimisation loops of the boot are presented in Section 5.3.

5.2 DESIGN CRITERIA

Shoes are classified according to the activities in which they are used. Each activity type requires different kind of shoe properties. Boot is one type of shoe. This type of shoe requires high performance, good under high activity, excellent traction, lightness, power balance and return of energy, resistance to weather conditions and protection from wild outdoor activities.

The boot can be divided into two parts. The first part is the upper part that the foot is covered by thin material such as, brand or leather. The second part is the lower part, which can be divided into upper, middle, and lower sole. The first part of boot is an aesthetic part and it's not affecting the analysis. The second part of boot is the main part of boot. If the upper, middle and lower soles are made from same materials, it is analysed as one part. Otherwise sole is analysed with different materials for each layer. This case is especially important for the special purposes.

5.3 ANALYSIS AND OPTIMISATION

5.3.1 Problem Definition

The boot, which is modelled in Chapter 4, has been considered for the analysis and optimisation. At the analysis stage upper part of the model is removed and only three-dimensional sole model is considered. The sole of boot is modelled with three layers and a heel. In the following section material properties, loading, boundary conditions, and optimisation parameters are defined.

5.3.2 Material Properties

For ANSYS Finite Element package program, material properties, which are modulus of elasticity and Poisson's ratio must be given to analyse the models. The general material properties of sole are given in Appendix A. These material properties are obtained from tension test and material handbook. The test has been done with INSTRON Testing Machine, which is shown in Figure 5.1. Typical test results of PVC are given in Appendix B.

In the analysis and optimisation, two types of material definition is used.

- In all layers and heel, same material properties are defined. In other words sole is made of one material.
- In each layers and heel, different material properties are defined which means that sole is made of more than one material.

5.3.3 Loading

Loading of the boot varies with shoe size, and weight distribution of the user. In the real life, the weight of the user is not linearly distributed over the sole and distribution is varied with time and the position of foot.

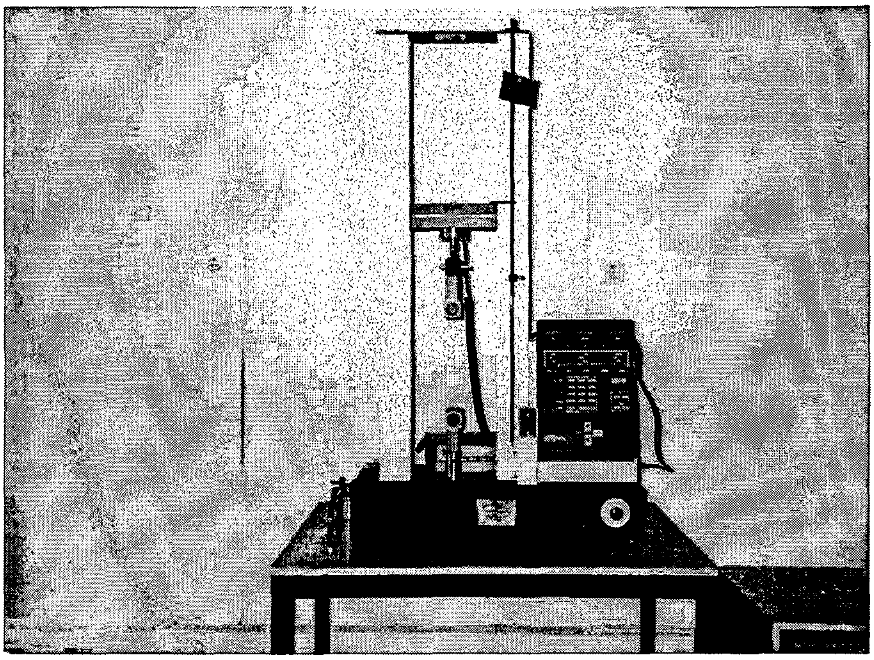


Figure 5.1 INSTRON Testing Machine

In order to analyse the shoe sole under various loading conditions certain type of approaches can be used. In this study, it is assumed that user at standing position and load of the user is taken 70 kg. As described in [2], the user weight is distributed as 25, 15, 30 kg over the three regions which are midfoot, forefoot and centre of heel respectively. Loading is shown in Figure 5.2.

5.3.4 Boundary Conditions

Boot sole is established on a rigid base. This problem is considered as rigid-elastic contact. Friction coefficient is considered as 0.4, which is given in [13] between boot sole and rigid base. A fixed boundary condition is applied to bottom of the rigid base in order to prevent movement and rotation as shown in Figure 5.2. No other boundary conditions are applied to the boot sole.

5.3.5 Optimisation

In the optimisation, design variables, objective function and constraints must be defined for the problem. Our design variables are sole thickness. These are t_1, t_2, t_3, and t_4 as shown in Figure 5.3.

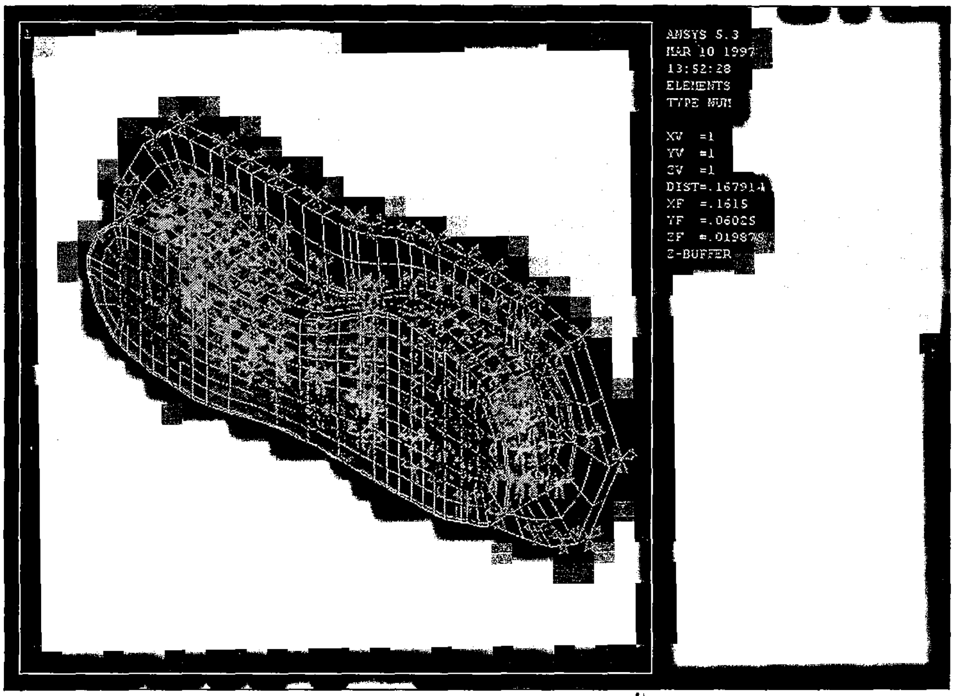


Figure 5.2 Loading and Boundary Conditions

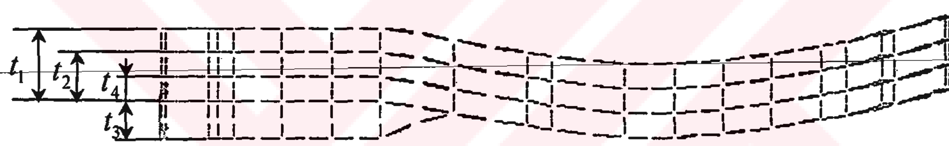


Figure 5.3 Layer Thicknesses

Due to geometric and manufacturing limitation upper and lower bounds are given for the design variables. These limits are;

$$15 \text{ mm} \leq t_1 \leq 40 \text{ mm}$$

$$15 \text{ mm} \leq t_2 \leq 20 \text{ mm}$$

$$8 \text{ mm} \leq t_3 \leq 15 \text{ mm}$$

$$6 \text{ mm} \leq t_4 \leq 10 \text{ mm}$$

The behaviour constraint is imposed on stresses. Maximum Von Misses stress should be less than yield stresses.

Two types of objective function is considered in optimisation:

- Minimisation of total volume and
- Minimisation of total strain.

5.3.6 Analysis and Optimisation Loop

After modelling of geometry and defining material properties, loading, boundary conditions and optimisation parameters, finite element analysis is carried out. The displacements and stresses are evaluated together with the objective function such as volume or strain energy of the sole. The finite element analysis is performed for 3-D rigid elastic contact.

Based on the current results of analysis a new sole geometry is generated with an improved value of objective function. This new design must satisfy the constraints if it is to be acceptable. If the convergence criterion for the optimisation algorithm is satisfied, the optimum solution has been found and process is terminated. Otherwise the optimisation process will continue by producing a sequence of new designs until an optimal solution is obtained.

5.4 RESULTS OF ANALYSIS

Initial results of analysis are given in Figure 5.4-5.15. Optimisation results for minimisation of total volume, which is the objective function to get optimum sole thickness shown Figure 5.16-5.27. On the other hand optimised soles with objective function of total strain energy are shown in Figure 5.28-5.39.

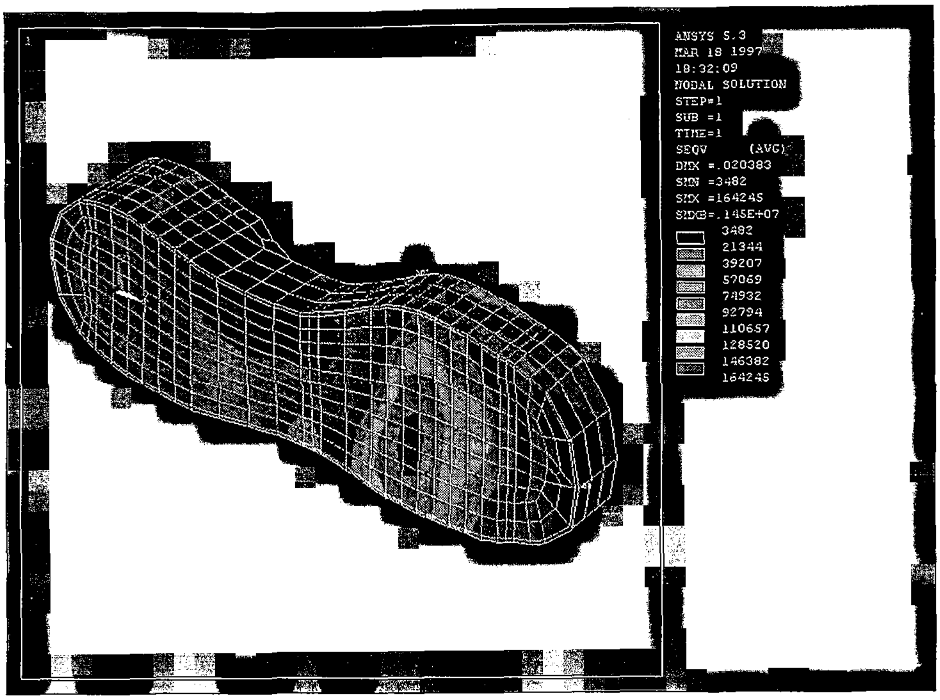


Figure 5.4 Equivalent Stress Distribution of Chloropene Pur Gum

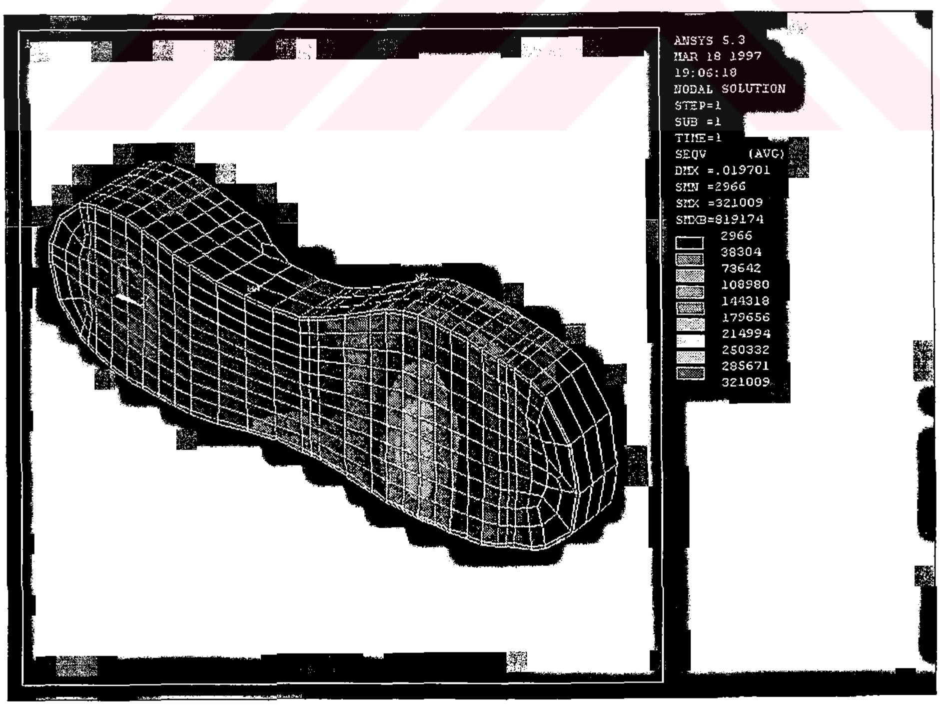


Figure 5.5 Equivalent Stress Distribution of Chloropene Vulcanise Cost

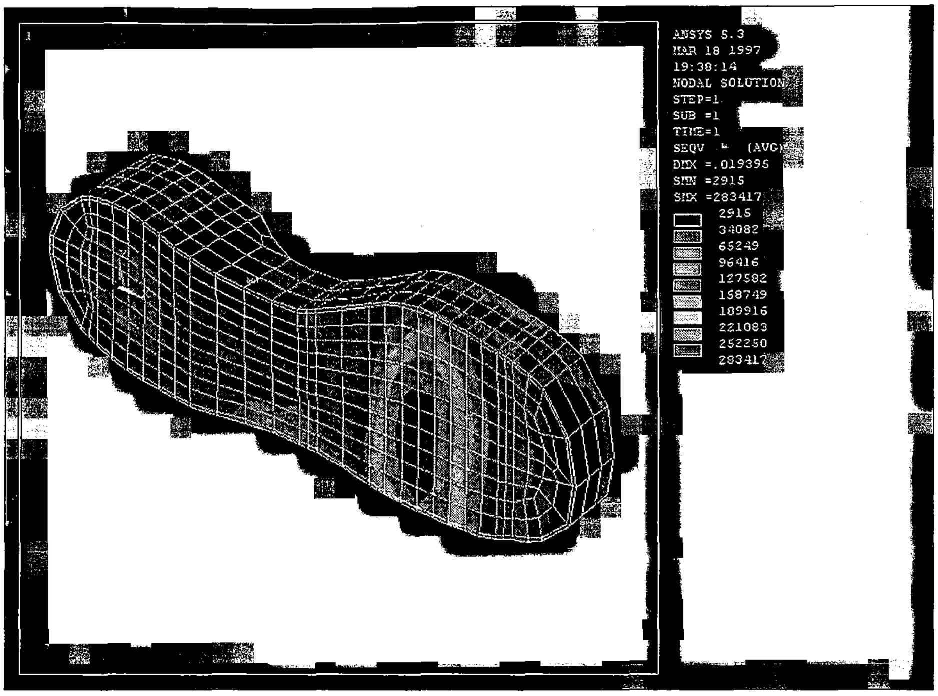


Figure 5.6 Equivalent Stress Distribution of Natural Rubber

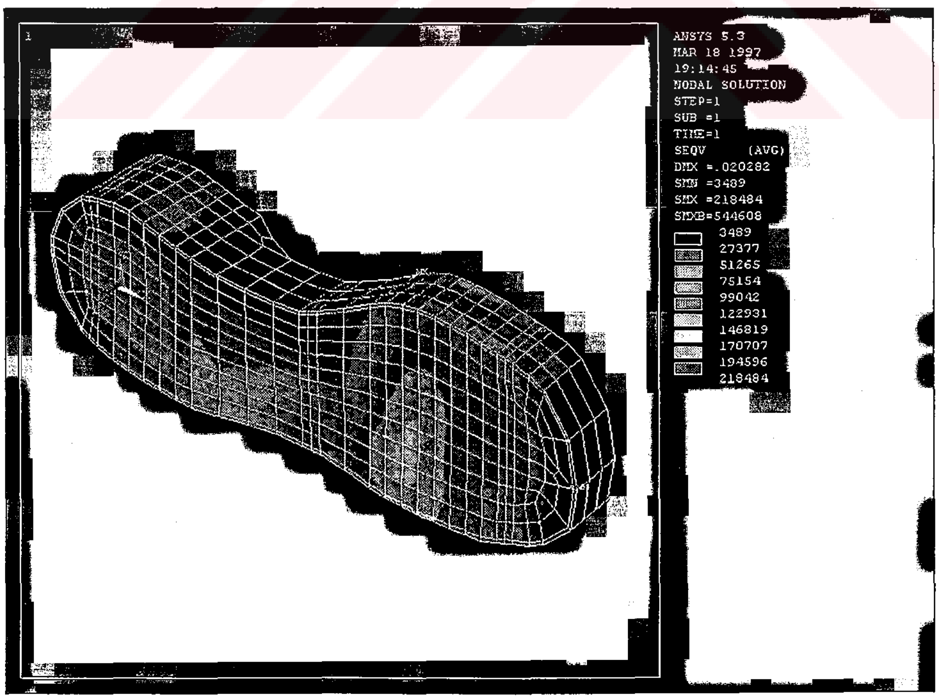


Figure 5.7 Equivalent Stress Distribution of Hard Rubber

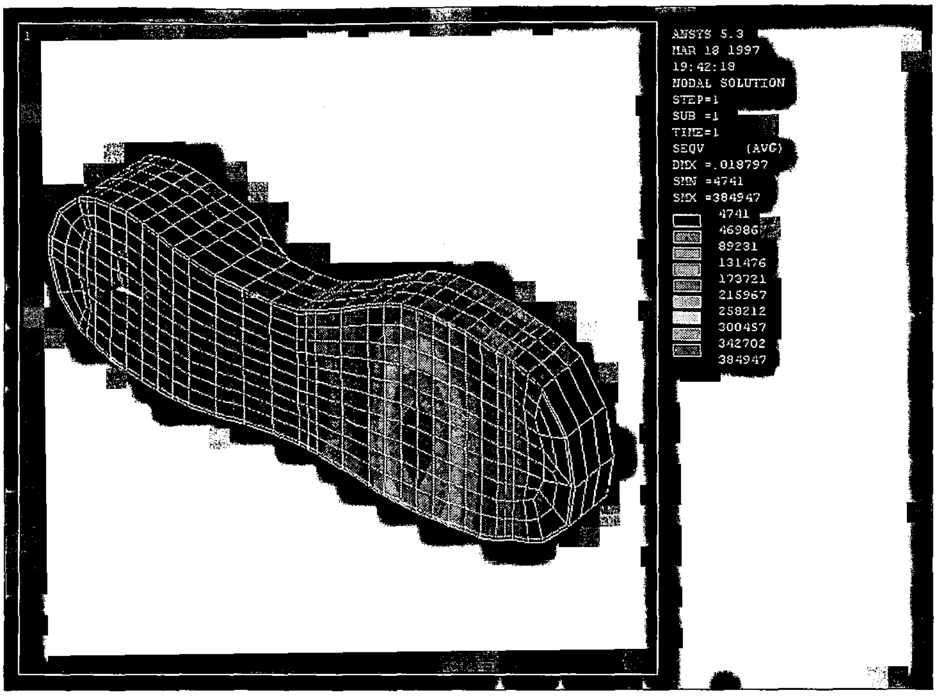


Figure 5.8 Equivalent Stress Distribution of Polyvinyl Chloride (PVC)

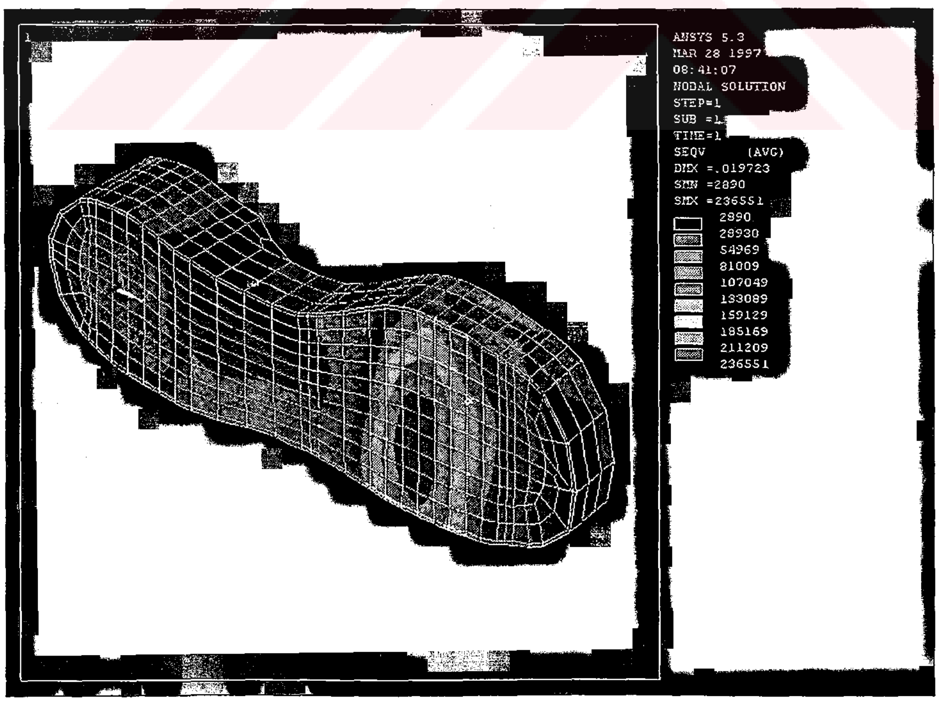


Figure 5.9 Equivalent Stress Distribution of Styrene Butadiene Rubber (SBR)

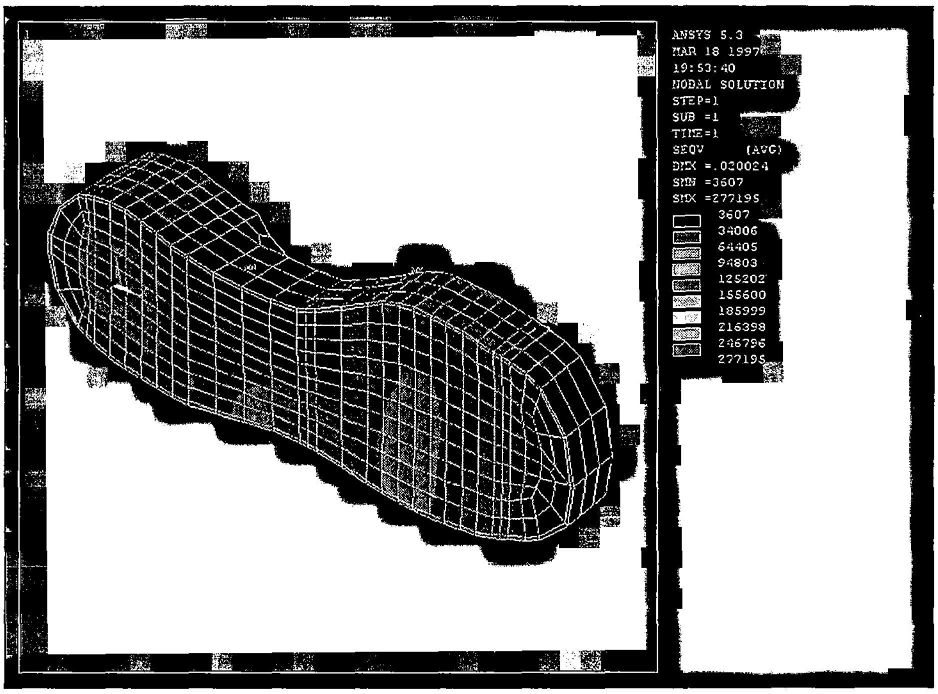


Figure 5.10 Equivalent Stress Distribution of Thermoplastic Rubber

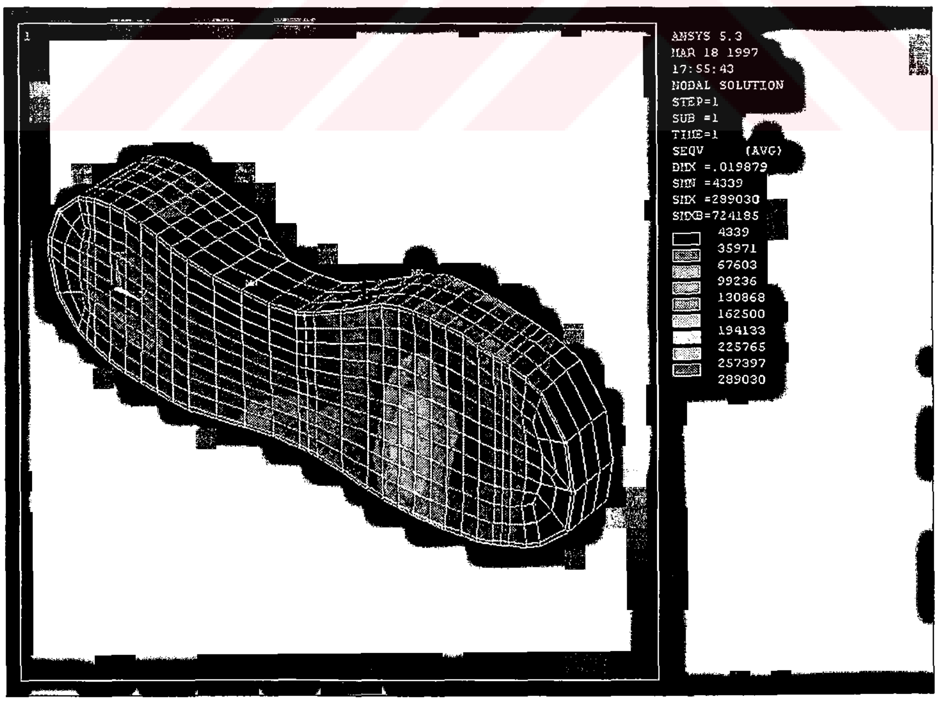


Figure 5.11 Equivalent Stress Distribution of Poured Polyurethane

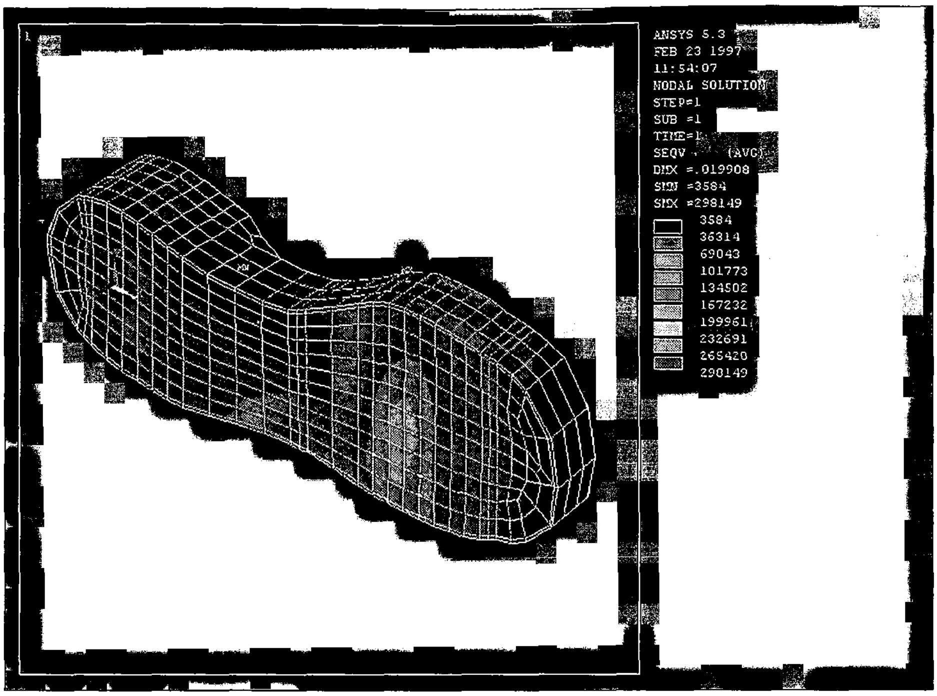


Figure 5.12 Equivalent Stress Distribution of the Sole (Upper sole: Polyurethane, Midsole: Natural Rubber, Heel and Lower Sole: PVC)

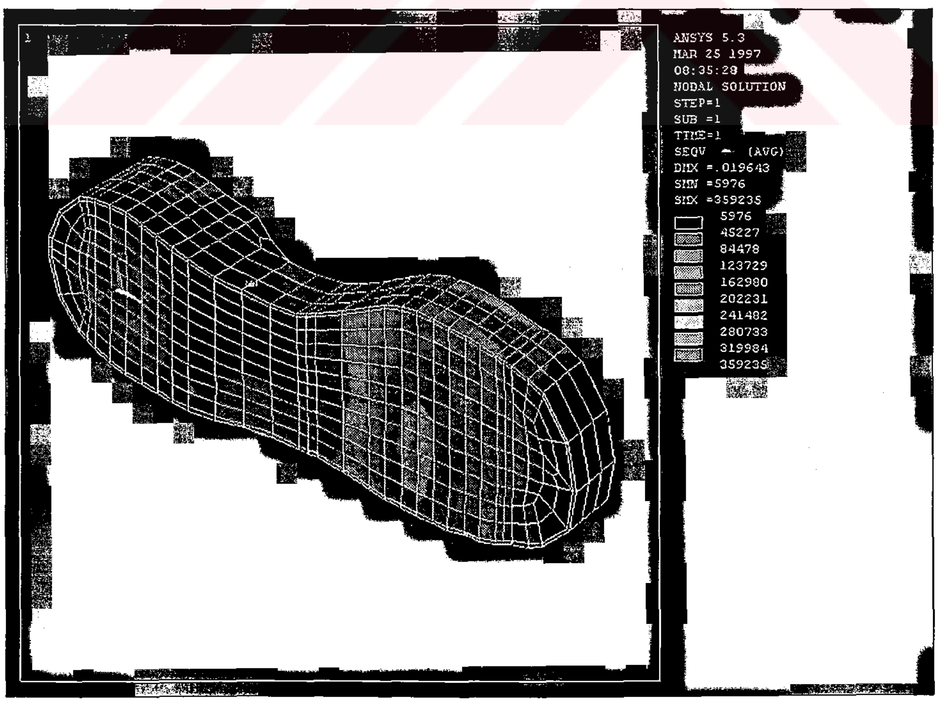


Figure 5.13 Equivalent Stress Distribution of the Sole (Upper sole: Polyurethane, Midsole: SBR, Heel and Lower Sole: Thermoplastic Rubber)

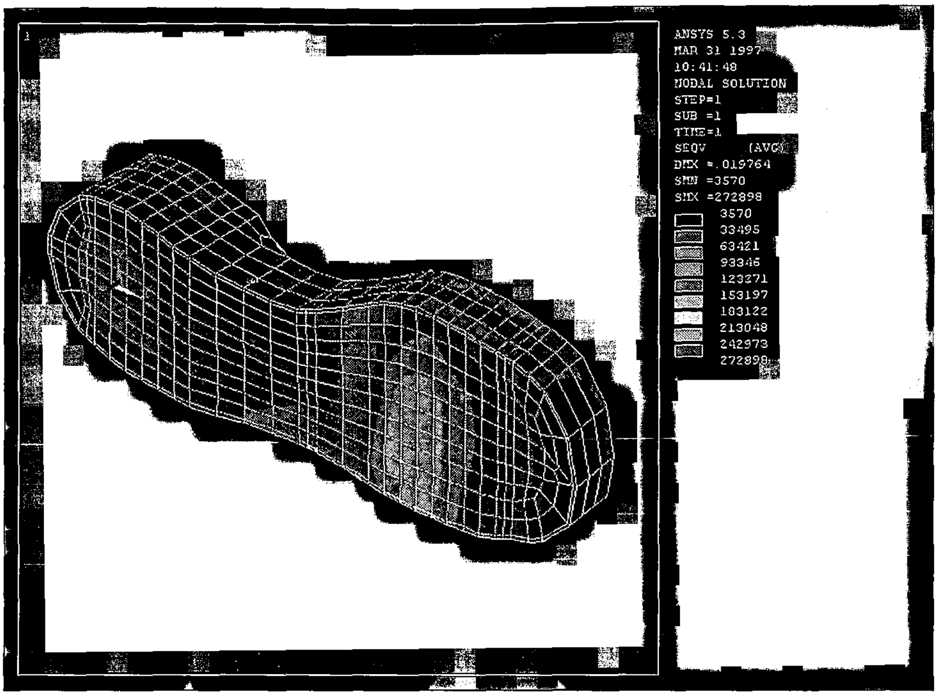


Figure 5.14 Equivalent Stress Distribution of the Sole (Upper sole: Polyurethane, Midsole: SBR, Heel and Lower Sole: Natural Rubber)

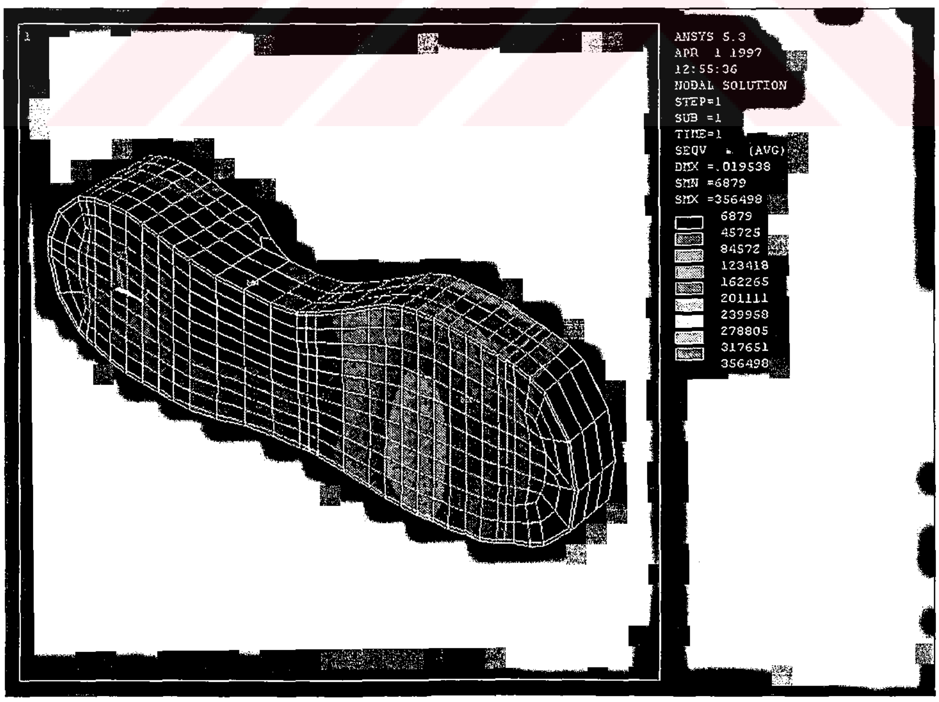
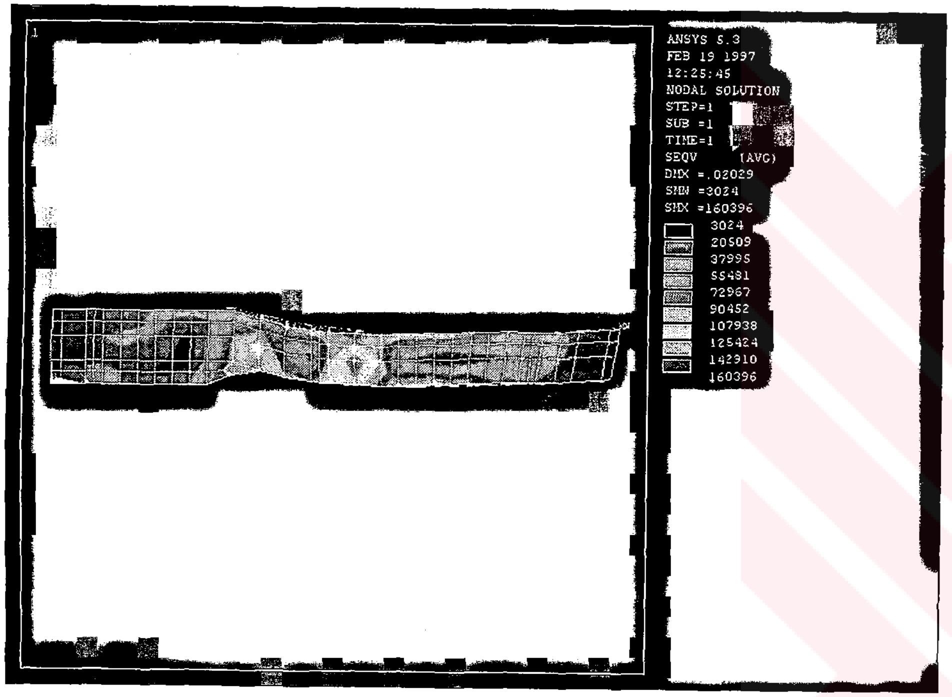
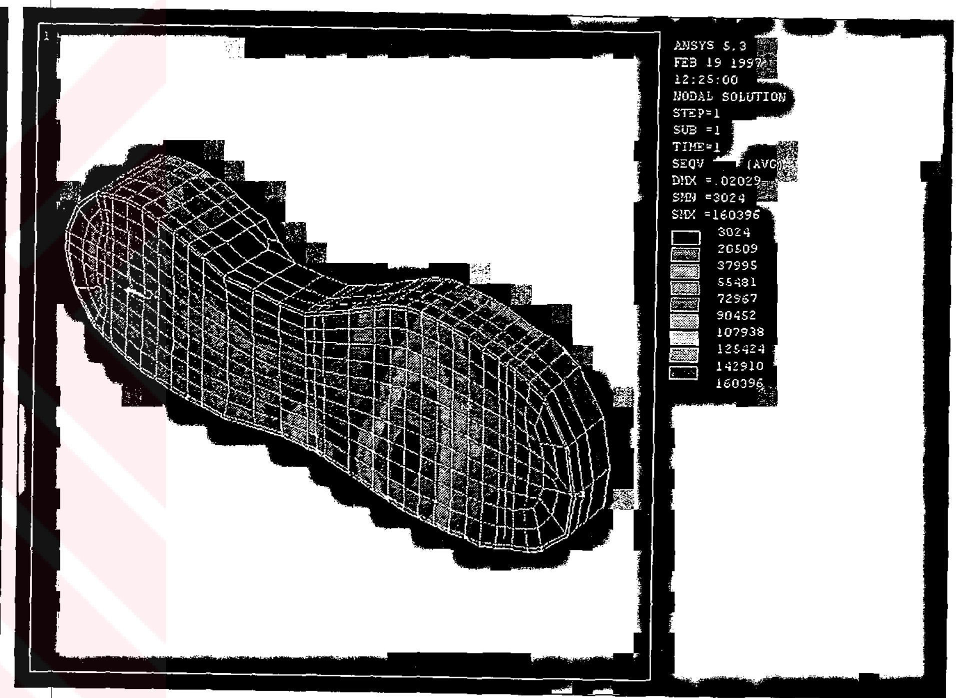


Figure 5.15 Equivalent Stress Distribution of the Sole (Upper sole: SBR, Midsole: Polyurethane, Heel and Lower Sole: PVC)

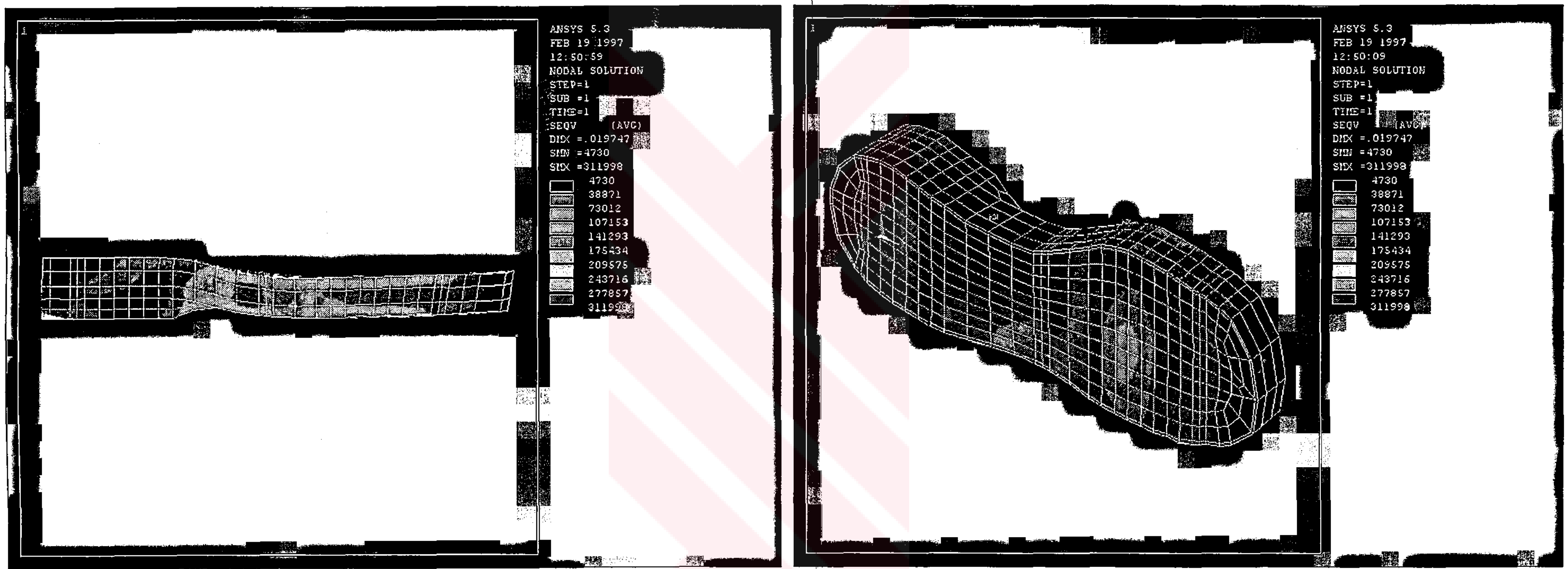


(a)



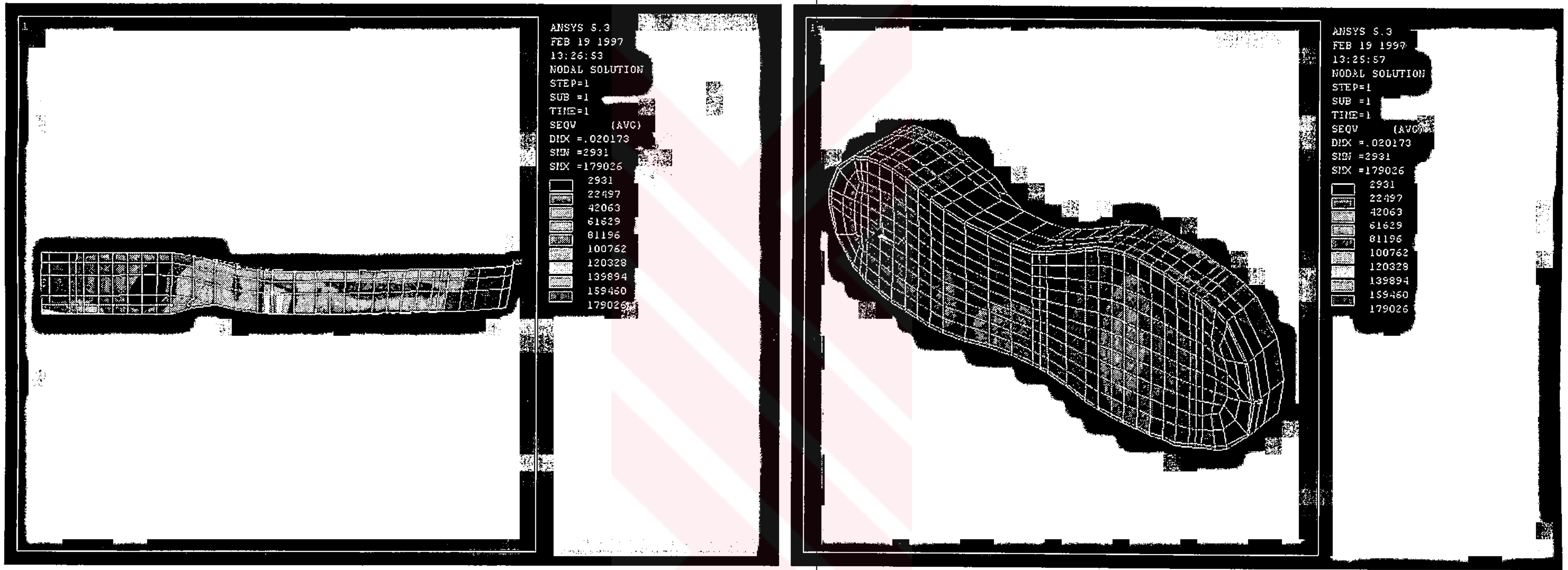
(b)

Figure 5.16 Equivalent Stress Distribution of Chloropene Pur Gum Sole After Optimisation with Objective Function of Total Volume (a) Bottom view, (b) Isometric view



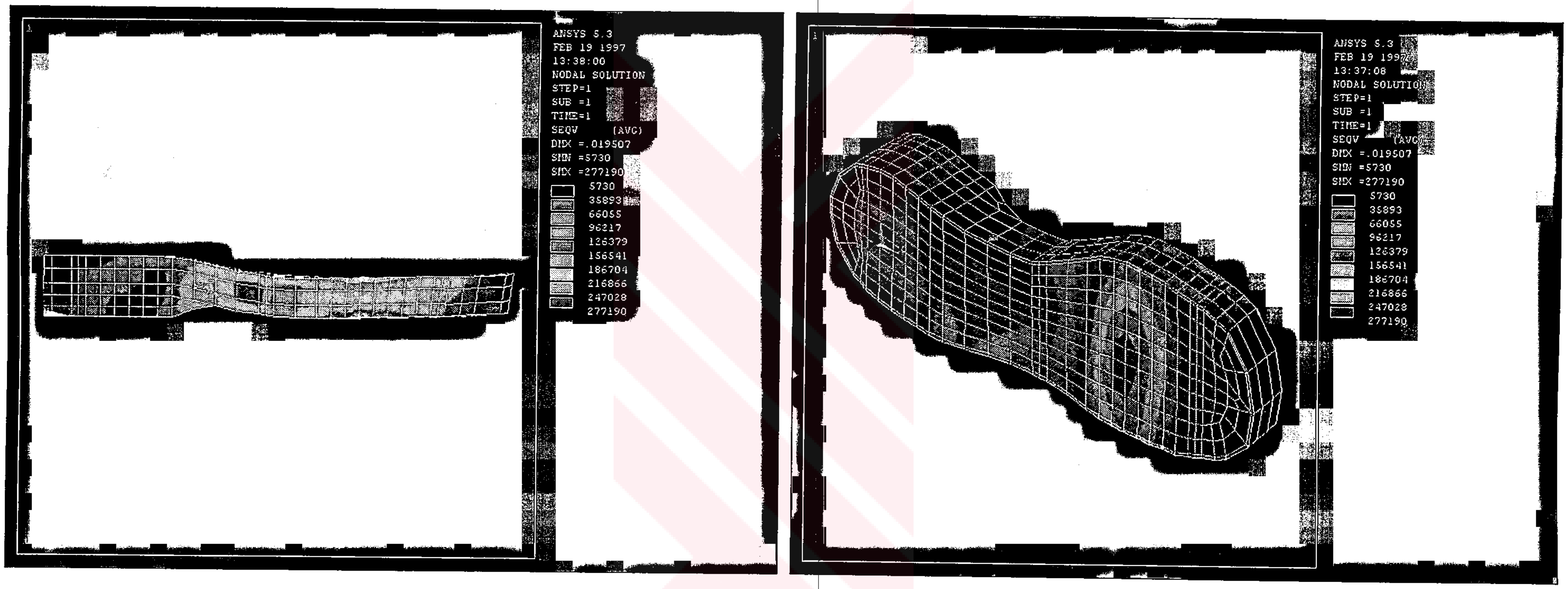
(a) (b)

Figure 5.17 Equivalent Stress Distribution of Chloropene Vul Cost Sole After Optimisation with Objective Function of Total Volume
(a) Bottom view, (b) Isometric view



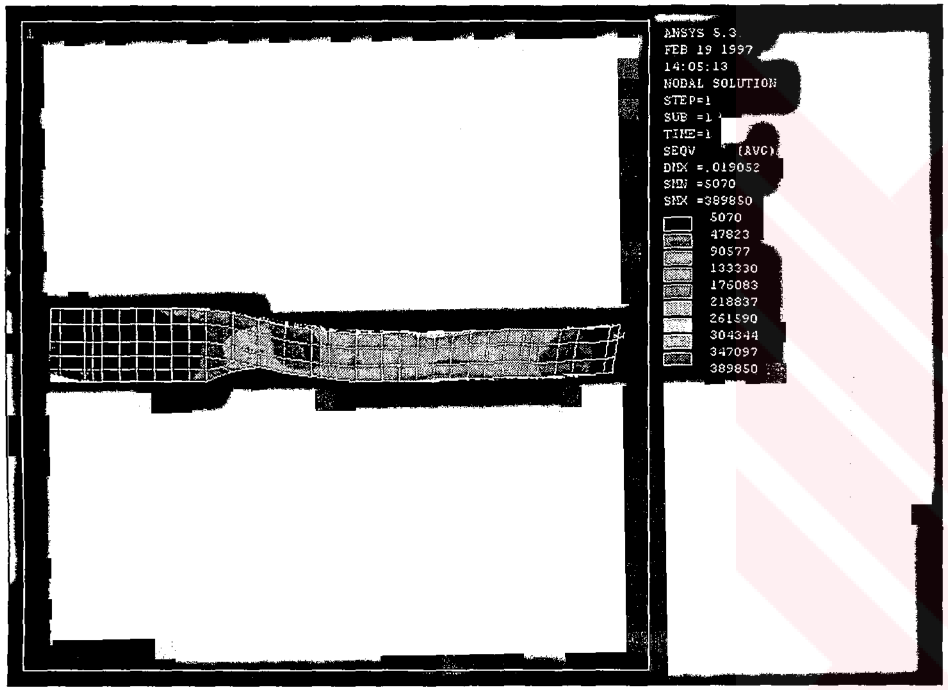
(a) (b)

Figure 5.18 Equivalent Stress Distribution of Hard Rubber Sole After Optimisation with Objective Function of Total Volume
(a) Bottom view, (b) Isometric view

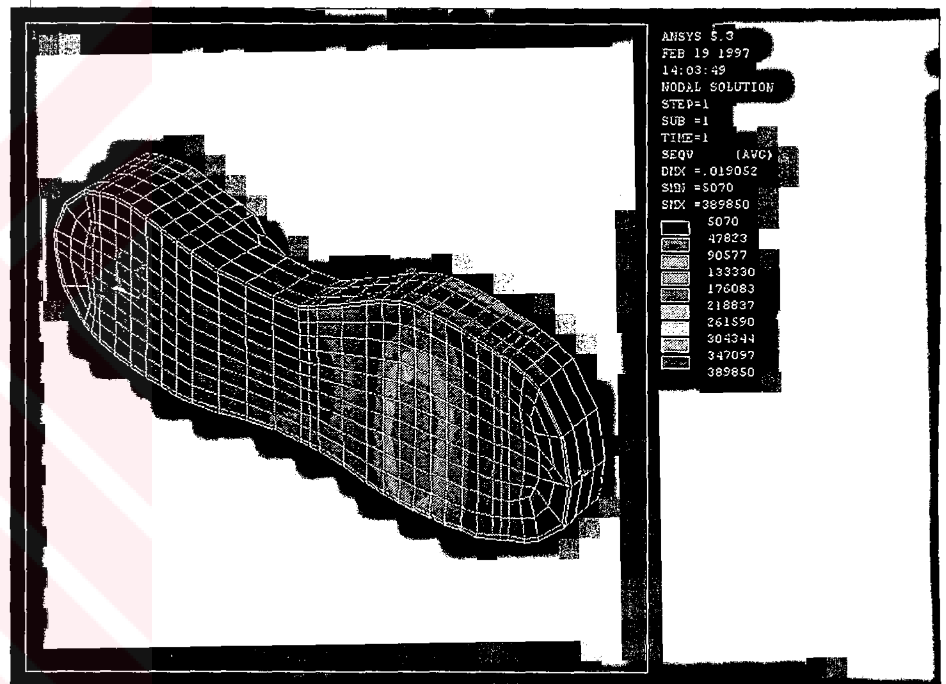


(a) (b)

Figure 5.19 Equivalent Stress Distribution of Natural Rubber Sole After Optimisation with Objective Function of Total Volume
(a) Bottom view, (b) Isometric view

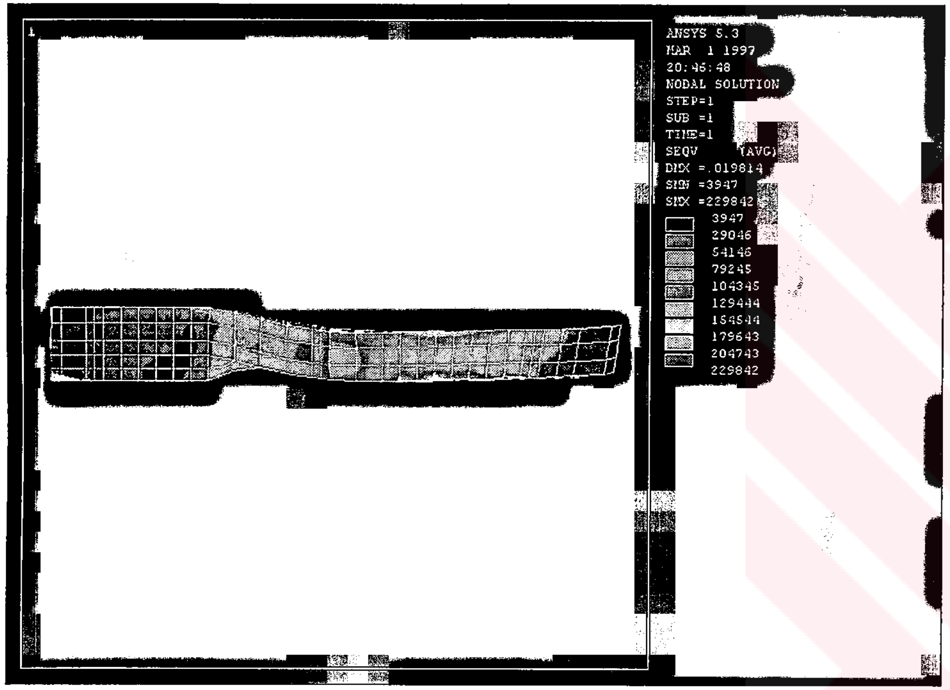


(a)

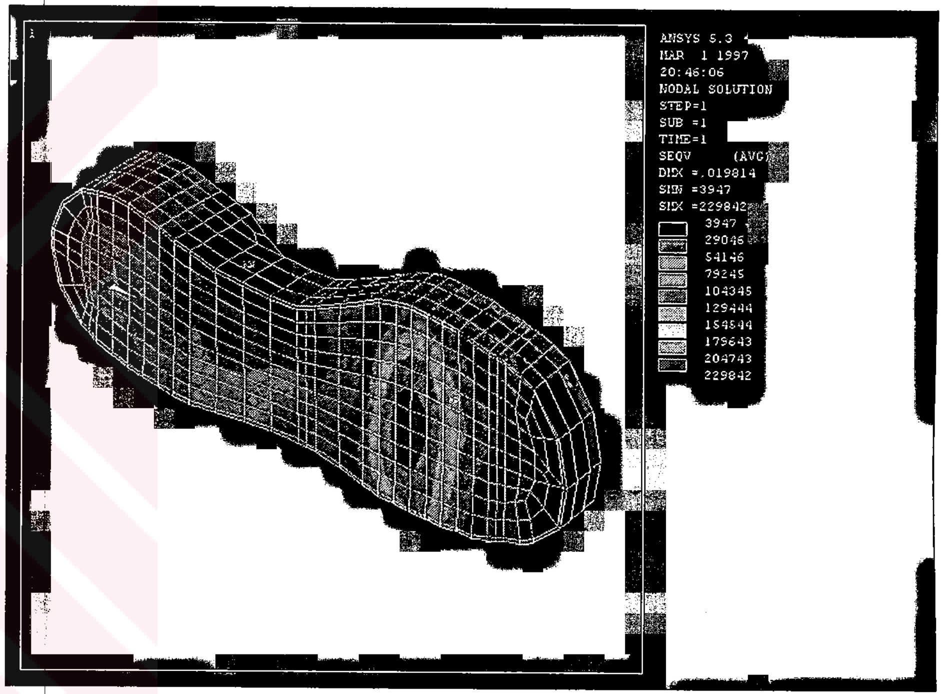


(b)

Figure 5.20 Equivalent Stress Distribution of PVC Sole After Optimisation with Objective Function of Total Volume
(a) Bottom view, (b) Isometric view

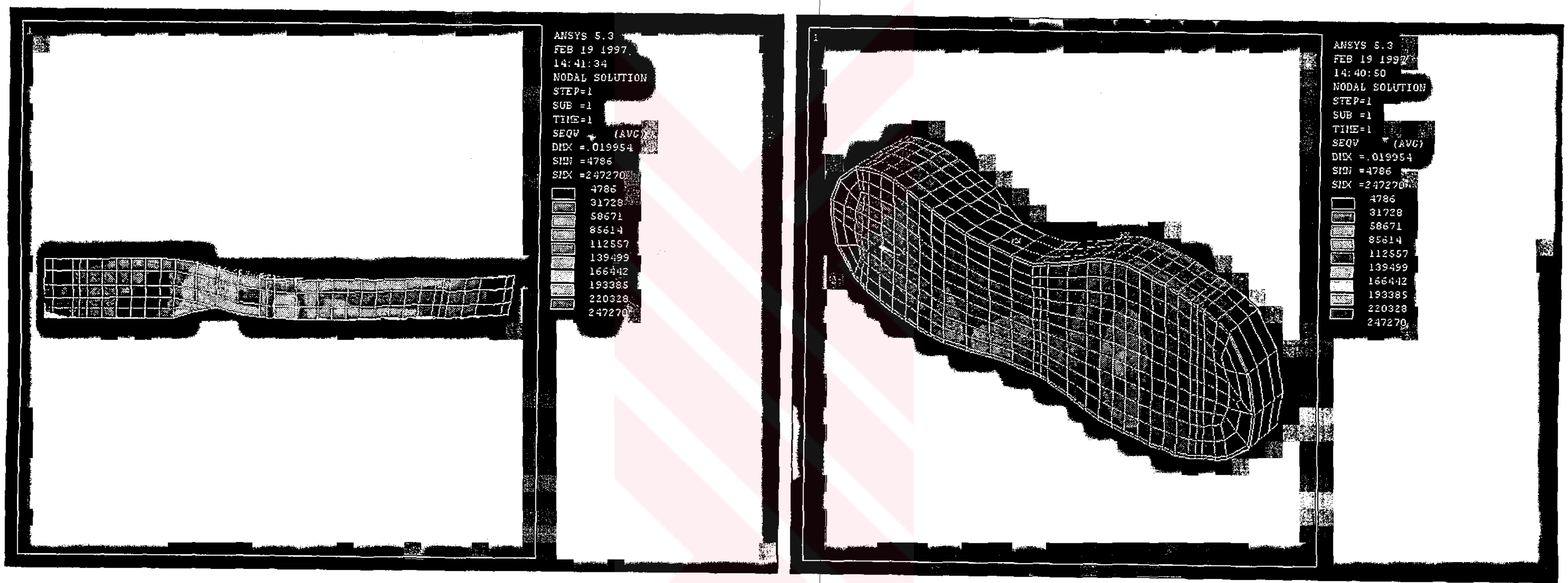


(a)



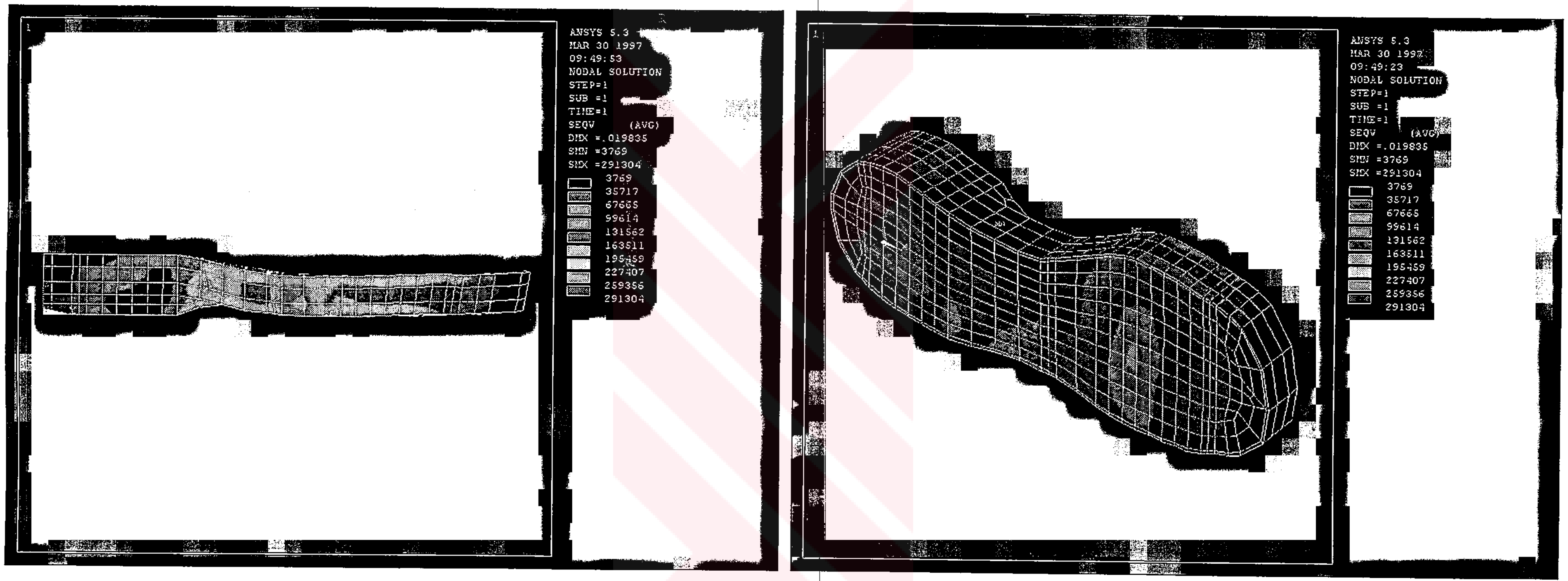
(b)

Figure 5.21 Equivalent Stress Distribution of SBR Sole After Optimised with Objective Function of Total Volume
(a) Bottom view, (b) Isometric view



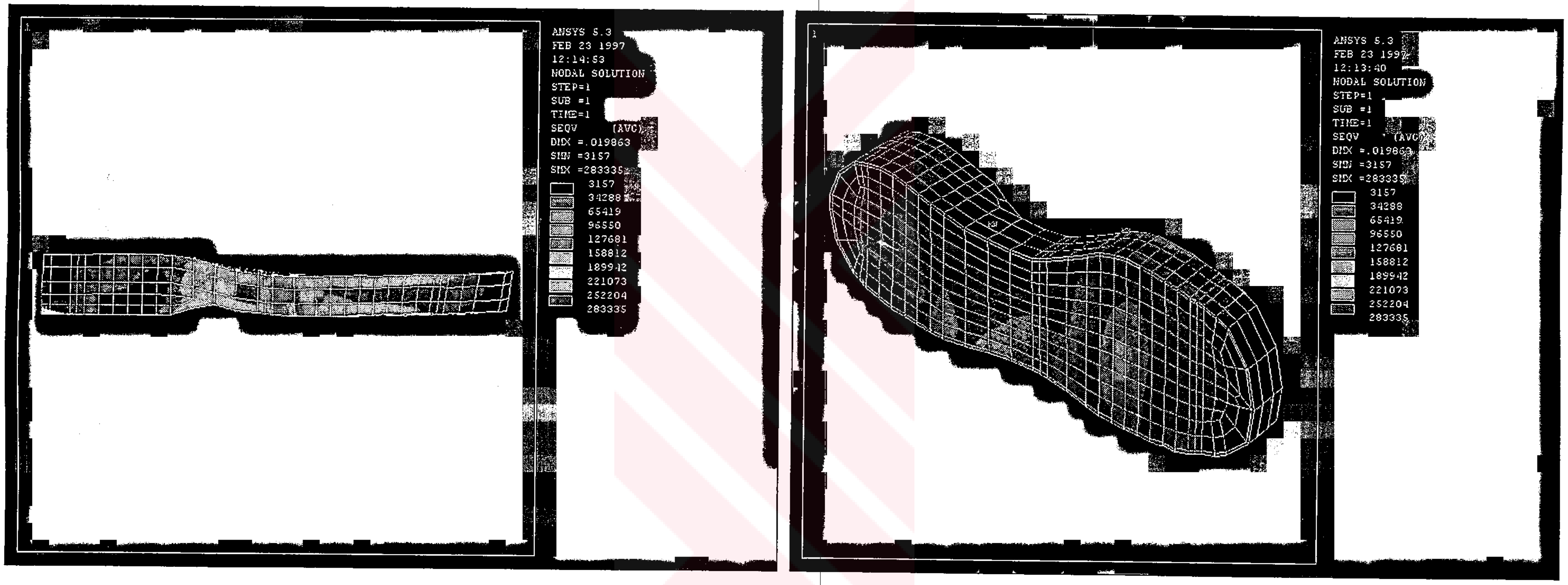
(a) (b)

Figure 5.22 Equivalent Stress Distribution of Thermoplastic Rubber Sole After Optimisation with Objective Function of Total Volume (a) Bottom view, (b) Isometric view



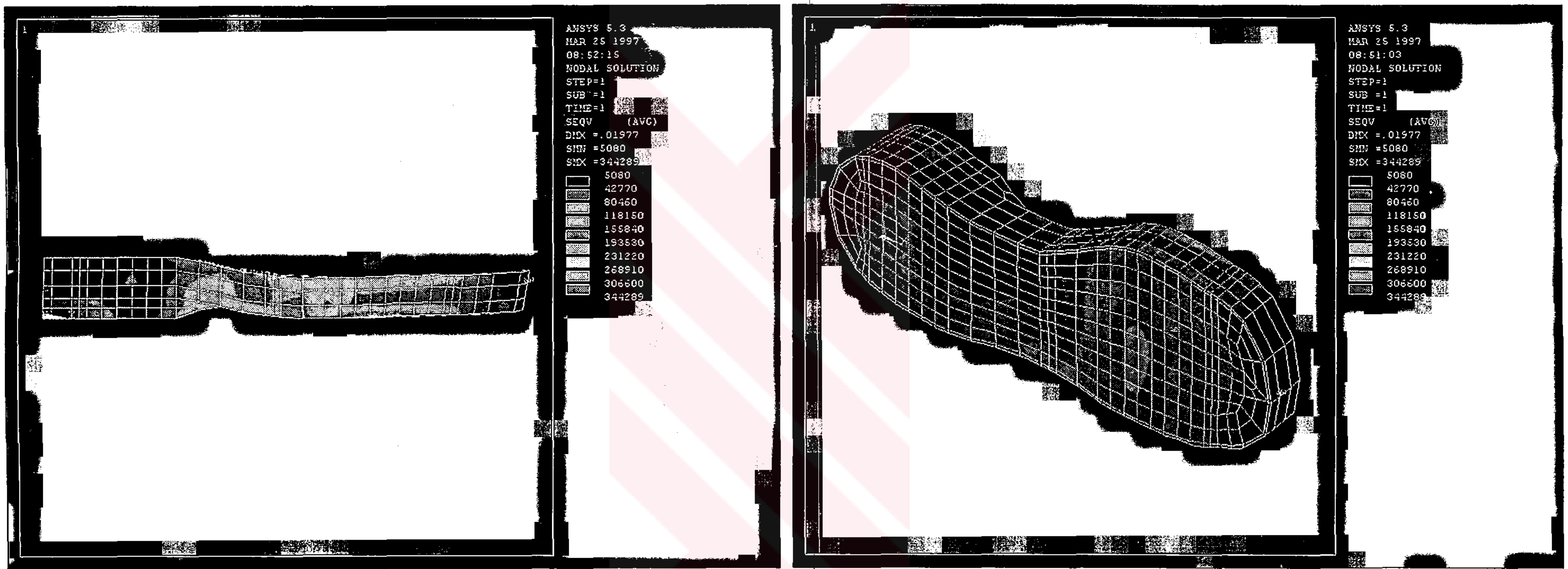
(a) (b)

Figure 5.23 Equivalent Stress Distribution of Poured Polyurethane Sole After Optimisation with Objective Function of Total Volume
(a) Bottom view, (b) Isometric view



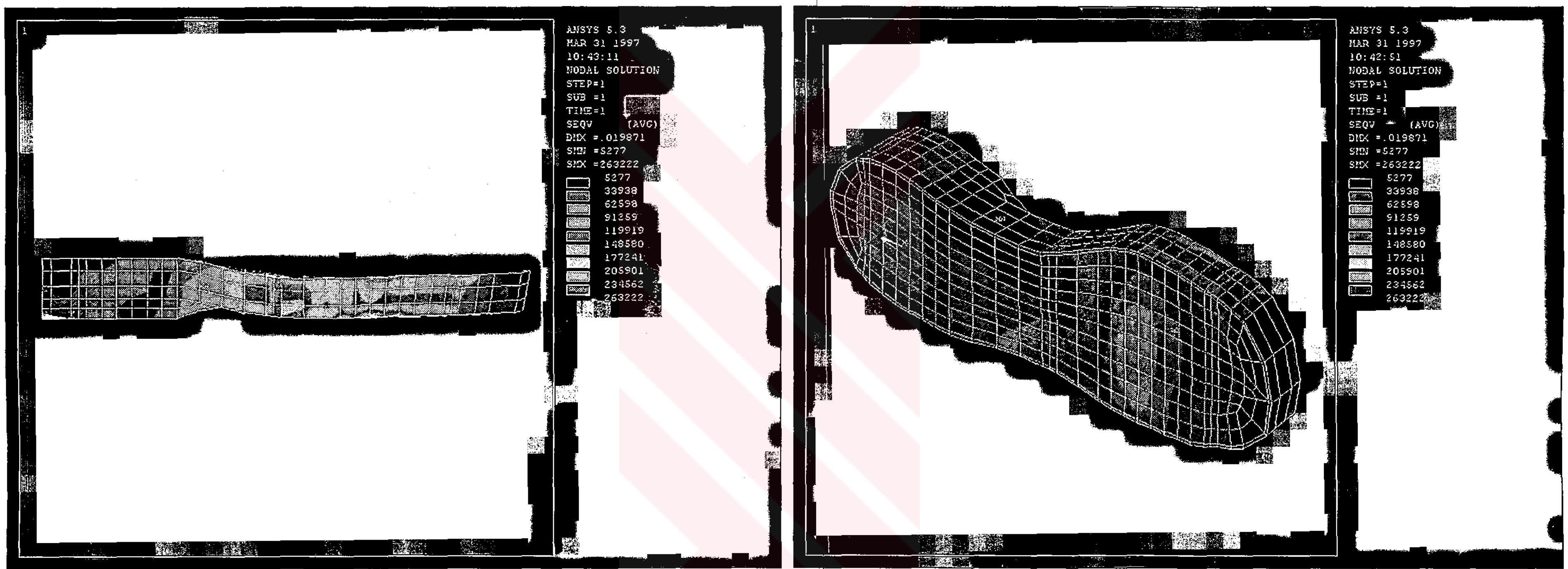
(a) (b)

Figure 5.24 Equivalent Stress Distribution of the Sole (Upper sole: Polyurethane, Midsole: Natural Rubber, Heel and Lower Sole: PVC) After Optimisation with Objective Function of Total Volume (a) Bottom view, (b) Isometric view



(a) (b)

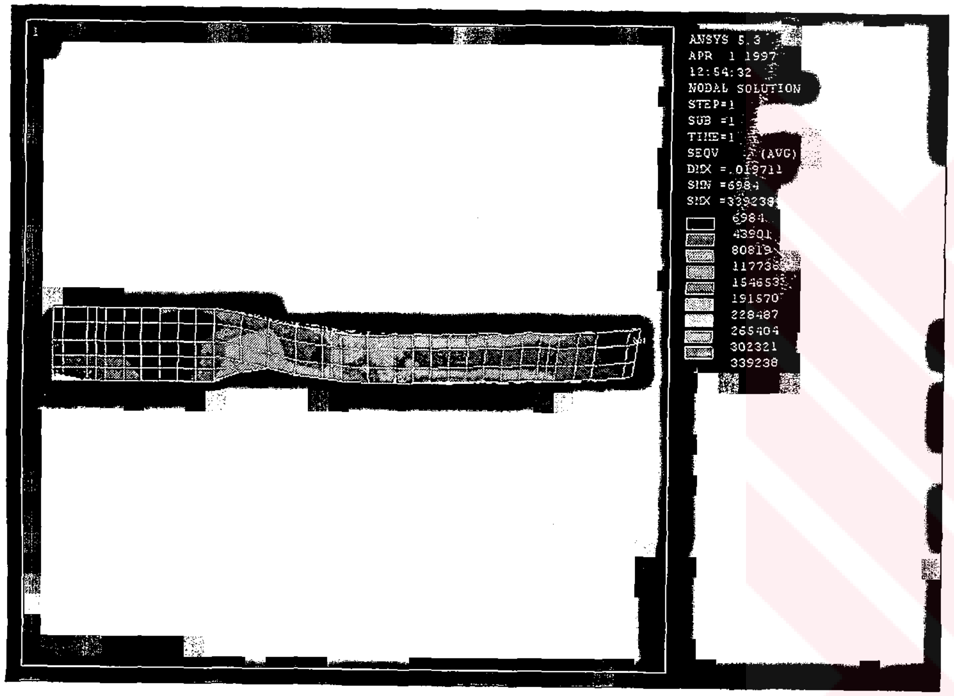
Figure 5.25 Equivalent Stress Distribution of the Sole (Upper sole: Polyurethane, Midsole: SBR, Heel and Lower Sole: Thermoplastic Rubber) After Optimisation with Objective Function of Total Volume (a) Bottom view, (b) Isometric view



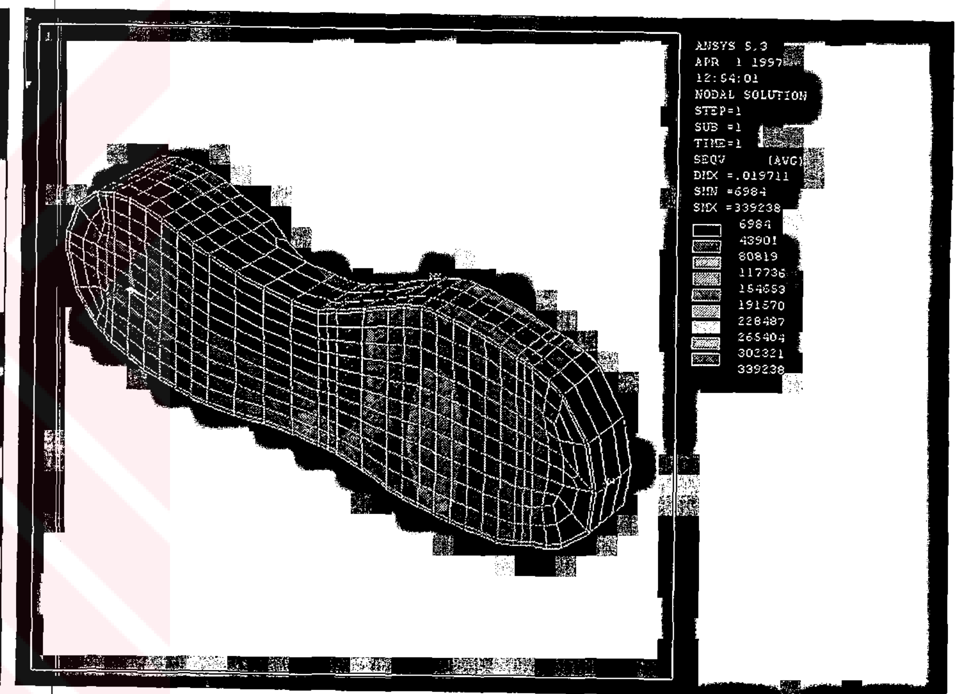
(a)

(b)

Figure 5.26 Equivalent Stress Distribution of the Sole (Upper sole: Polyurethane, Midsole: SBR, Heel and Lower Sole: Natural Rubber) After Optimisation with Objective Function of Total Volume (a) Bottom view, (b) Isometric view

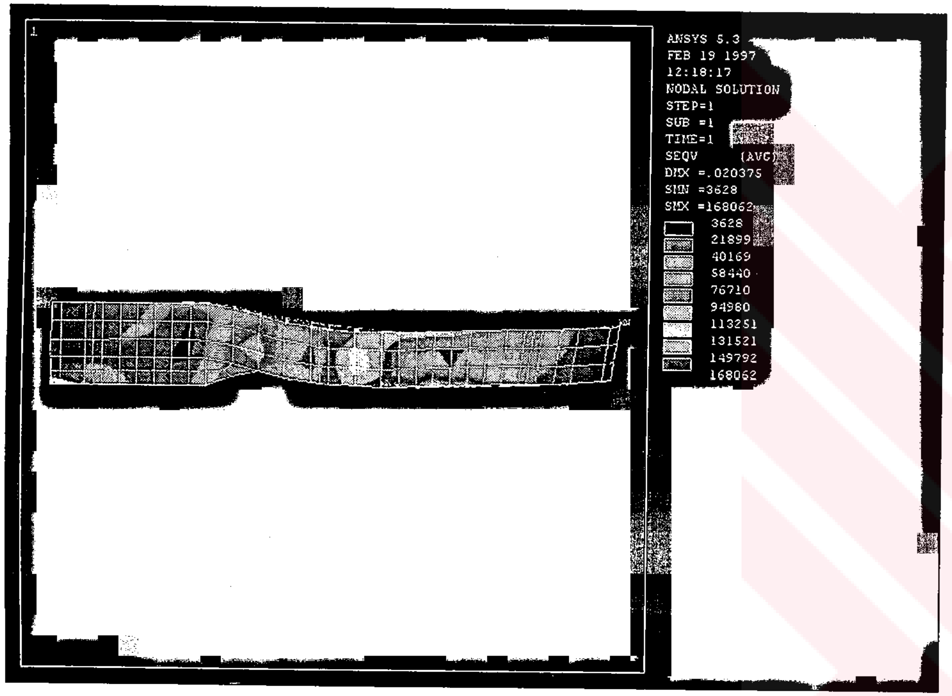


(a)

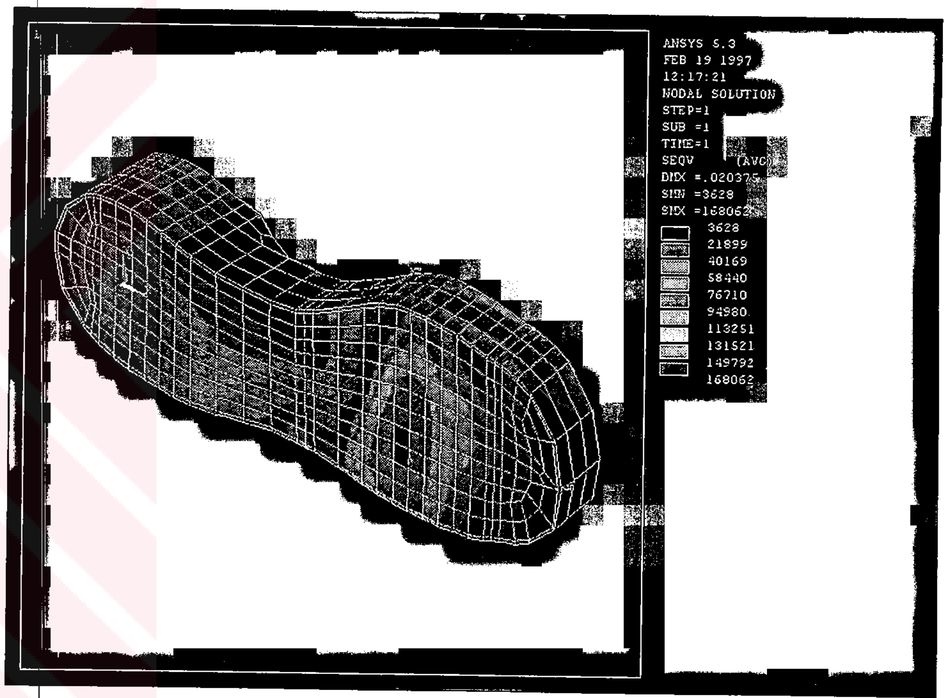


(b)

Figure 5.27 Equivalent Stress Distribution of the Sole (Upper sole: SBR, Midsole: Polyurethane, Heel and Lower Sole: Natural Rubber) After Optimisation with Objective Function of Total Volume (a) Bottom view, (b) Isometric view

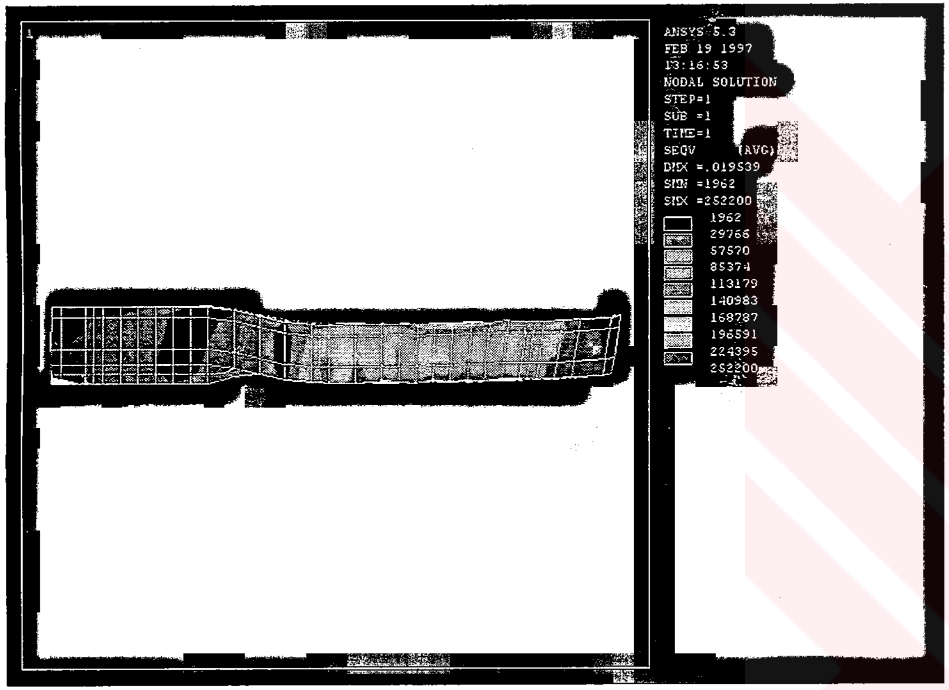


(a)

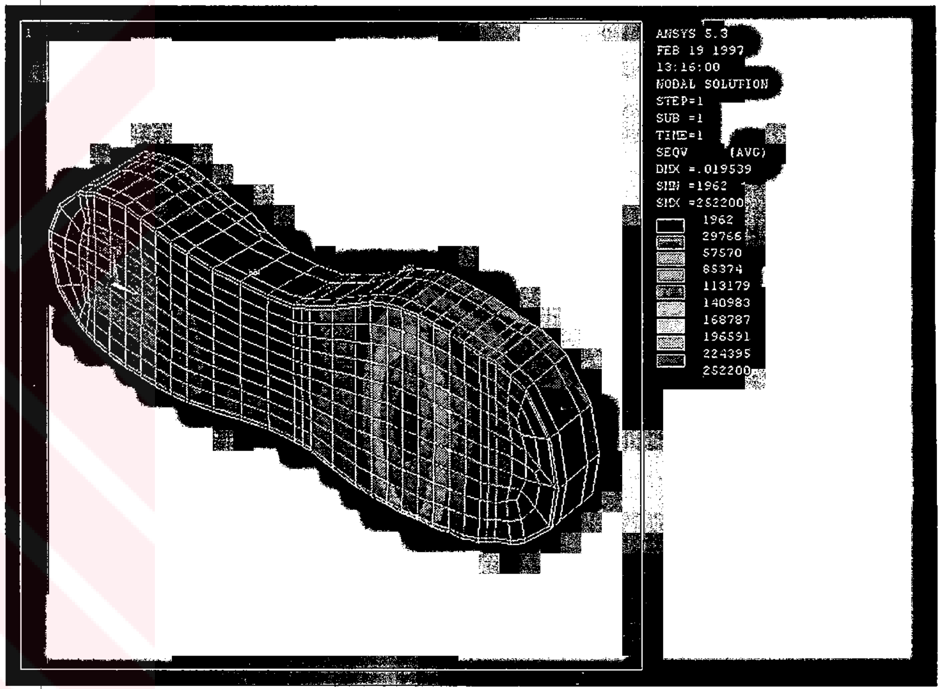


(b)

Figure 5.28 Equivalent Stress Distribution of Chloropene Pur Gum Sole After Optimisation with Objective Function of Total Strain Energy
(a) Bottom view, (b) Isometric view

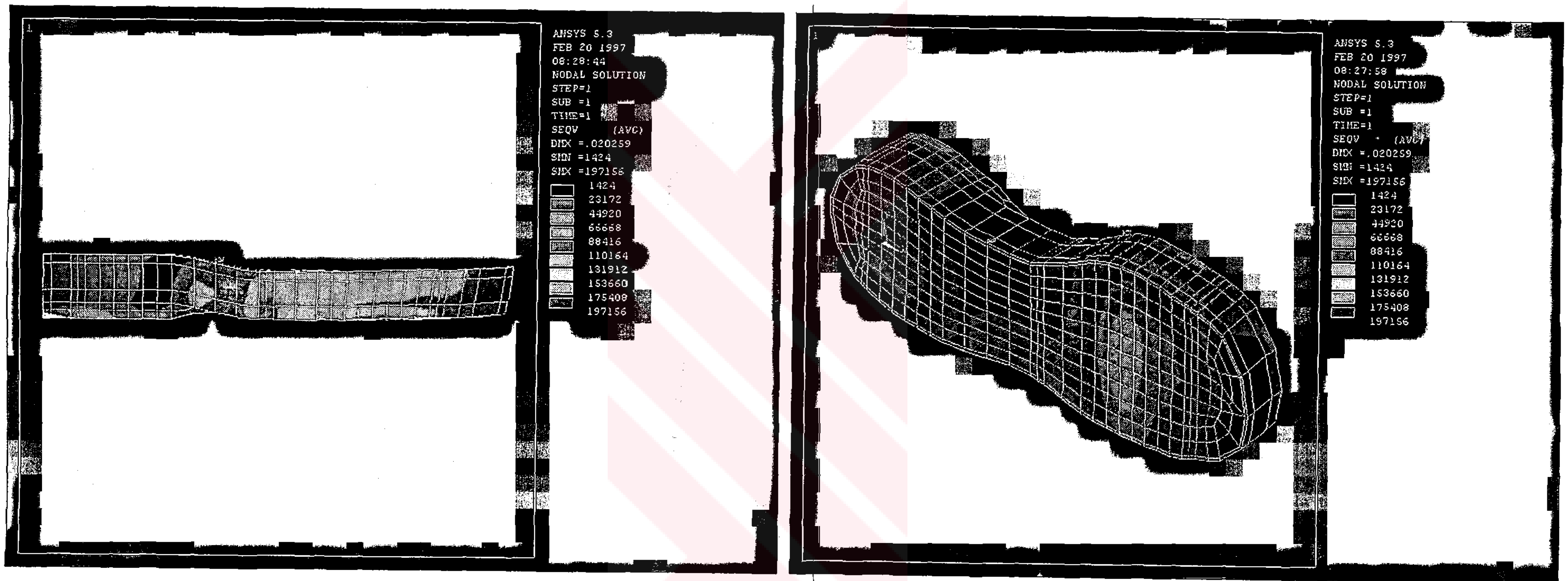


(a)



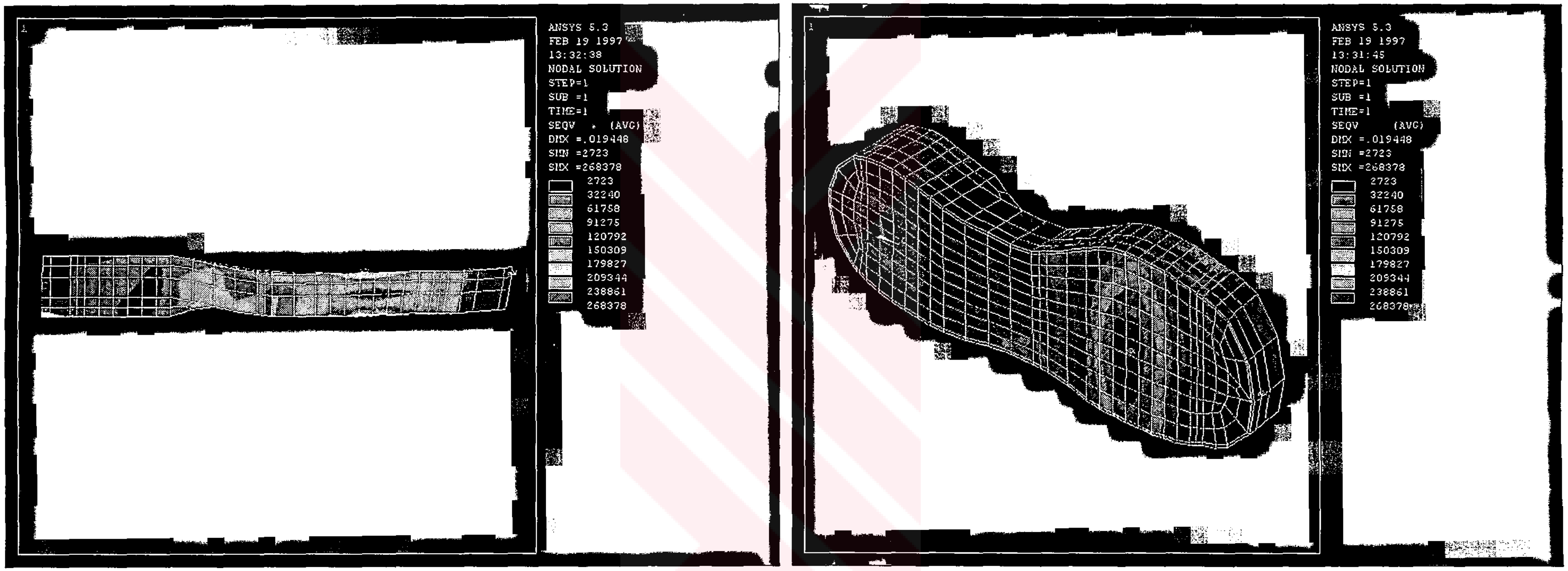
(b)

Figure 5.29 Equivalent Stress Distribution of Chloropene Vul Cost Sole After Optimisation with Objective Function of Total Strain Energy
(a) Bottom view, (b) Isometric view



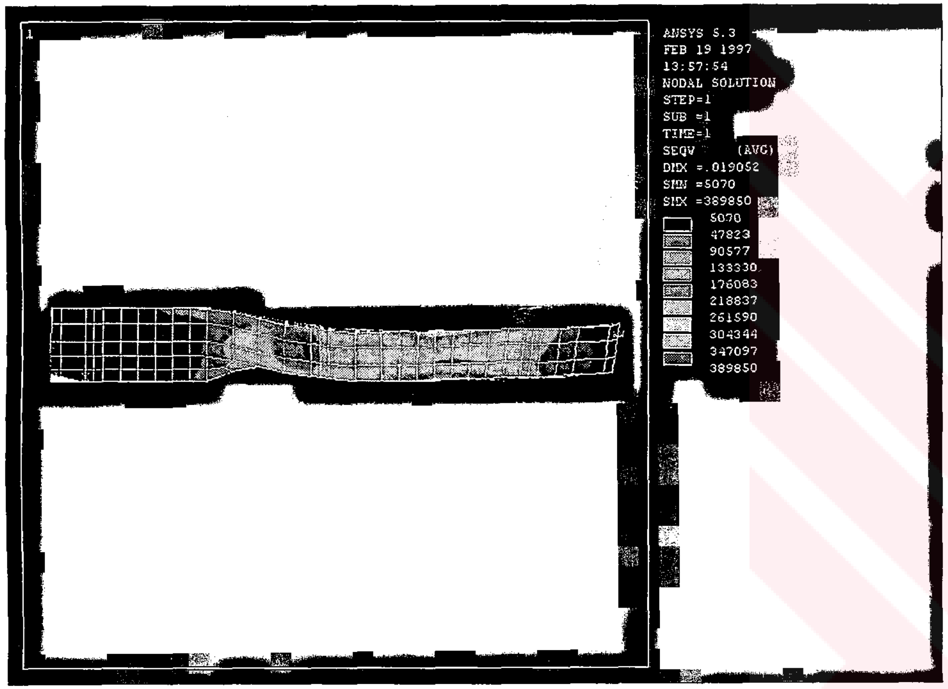
(a) (b)

Figure 5.30 Equivalent Stress Distribution of Hard Rubber Sole After Optimisation with Objective Function of Total Strain Energy
(a) Bottom view, (b) Isometric view

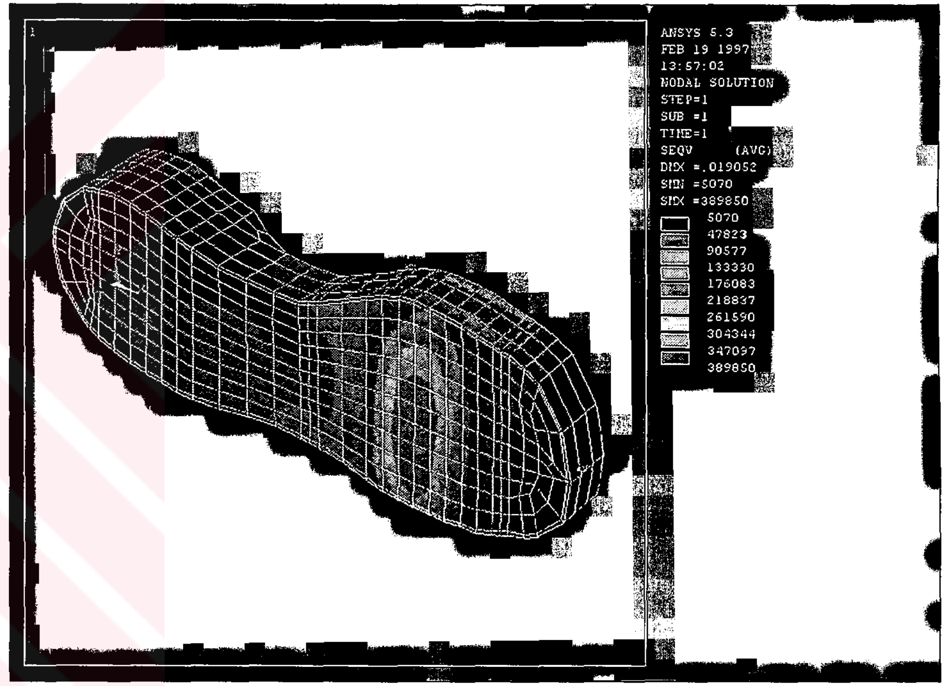


(a) (b)

Figure 5.31 Equivalent Stress Distribution of Natural Rubber Sole After Optimisation with Objective Function of Total Strain Energy
(a) Bottom view, (b) Isometric view

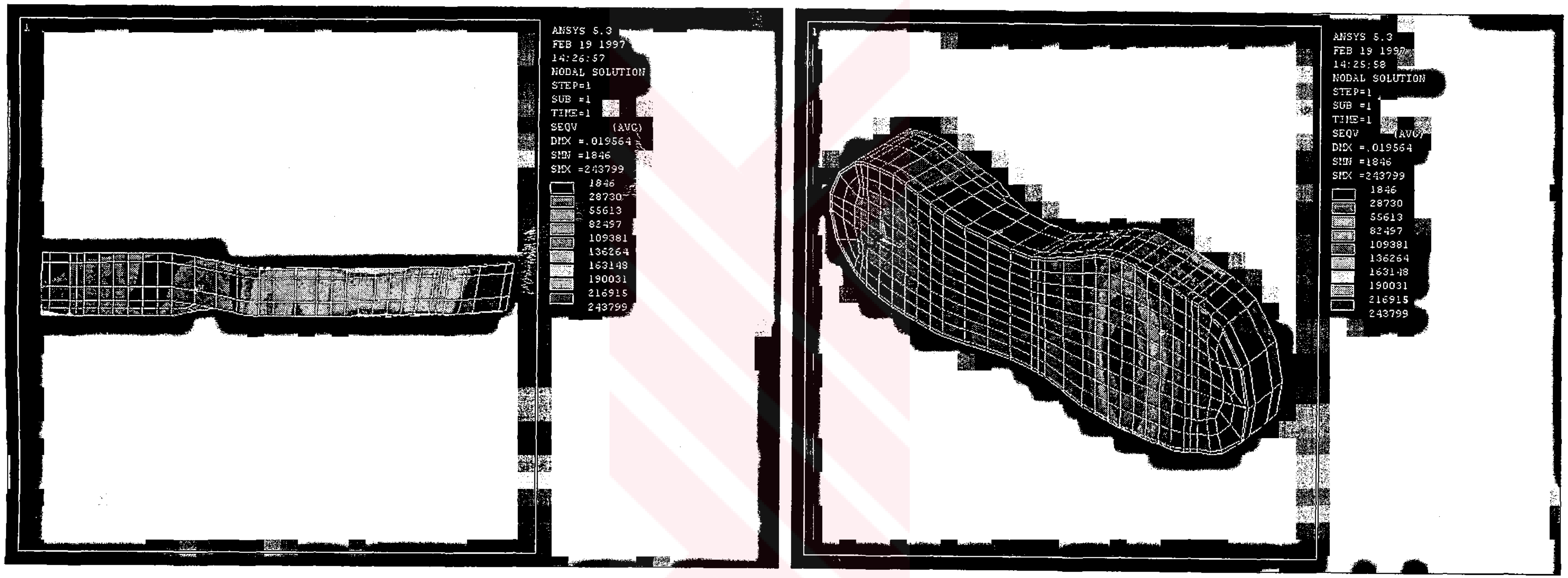


(a)



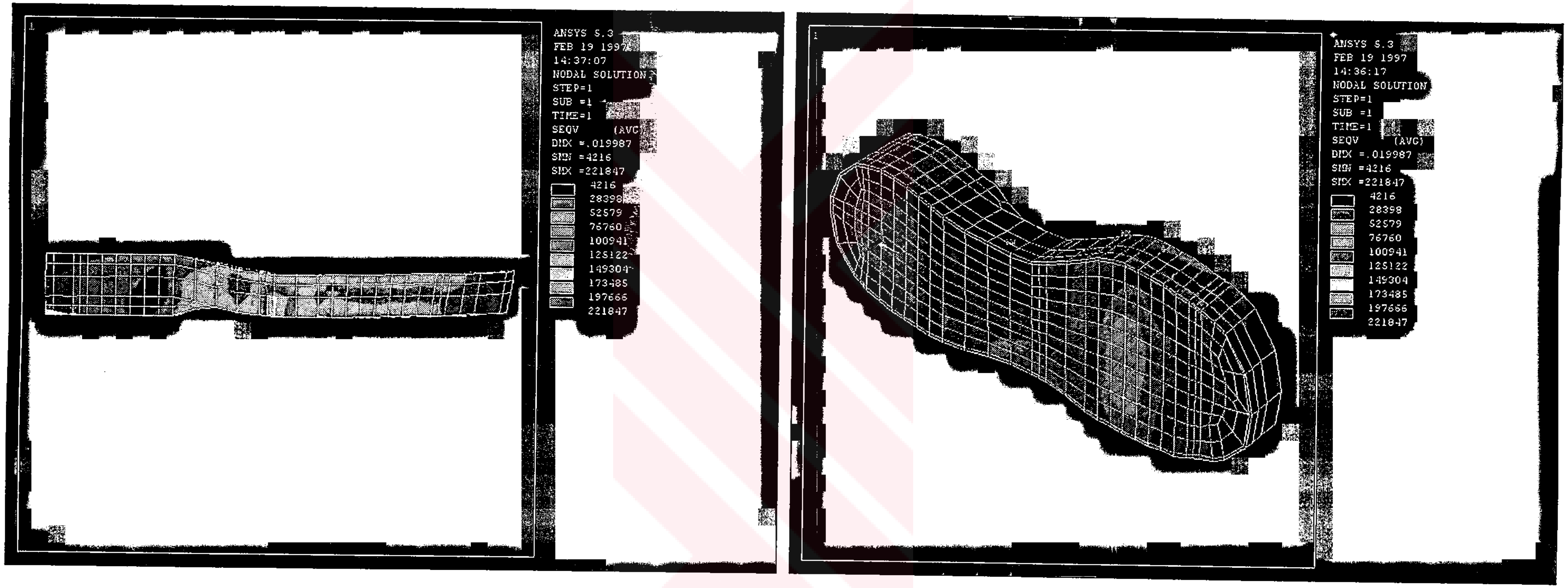
(b)

Figure 5.32 Equivalent Stress Distribution of PVC Sole After Optimisation with Objective Function of Total Strain Energy
(a) Bottom view, (b) Isometric view



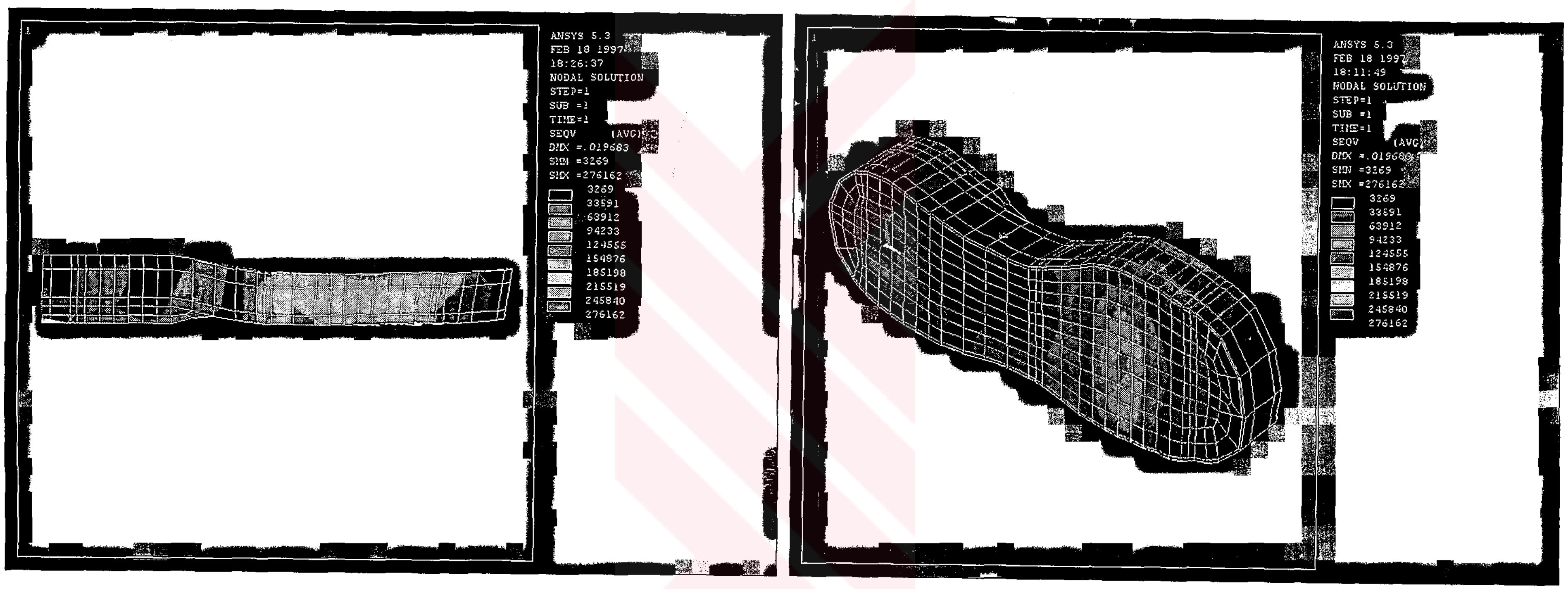
(a) (b)

Figure 5.33 Equivalent Stress Distribution of SBR Sole After Optimisation with Objective Function of Total Strain Energy
(a) Bottom view, (b) Isometric view



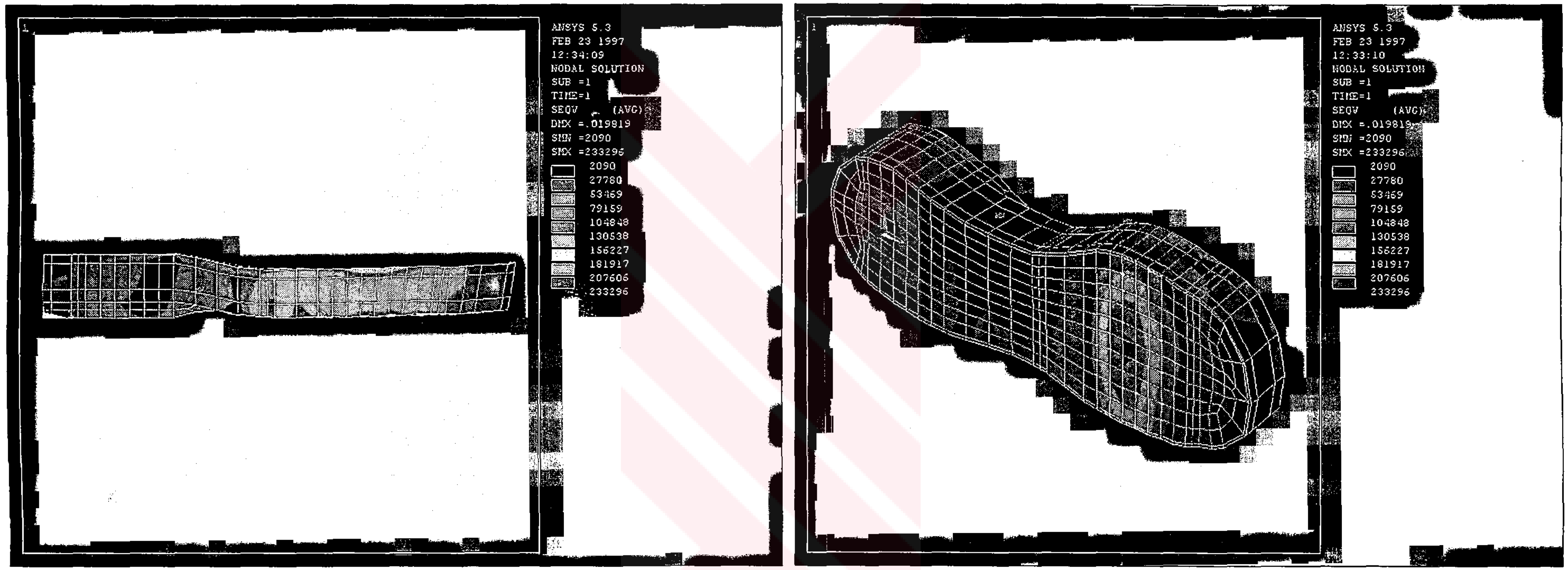
(a) (b)

Figure 5.34 Equivalent Stress Distribution of Thermoplastic Rubber Sole After Optimisation with Objective Function of Total Strain Energy
(a) Bottom view, (b) Isometric view



(a) (b)

Figure 5.35 Equivalent Stress Distribution of Poured Polyurethane Sole After Optimisation with Objective Function of Total Strain Energy
(a) Bottom view, (b) Isometric view



(a) (b)

Figure 5.36 Equivalent Stress Distribution of the Sole (Upper sole: Polyurethane, Midsole: Natural Rubber, Heel and Lower Sole: PVC) After Optimisation with Objective Function of Total Strain Energy (a) Bottom view, (b) Isometric view

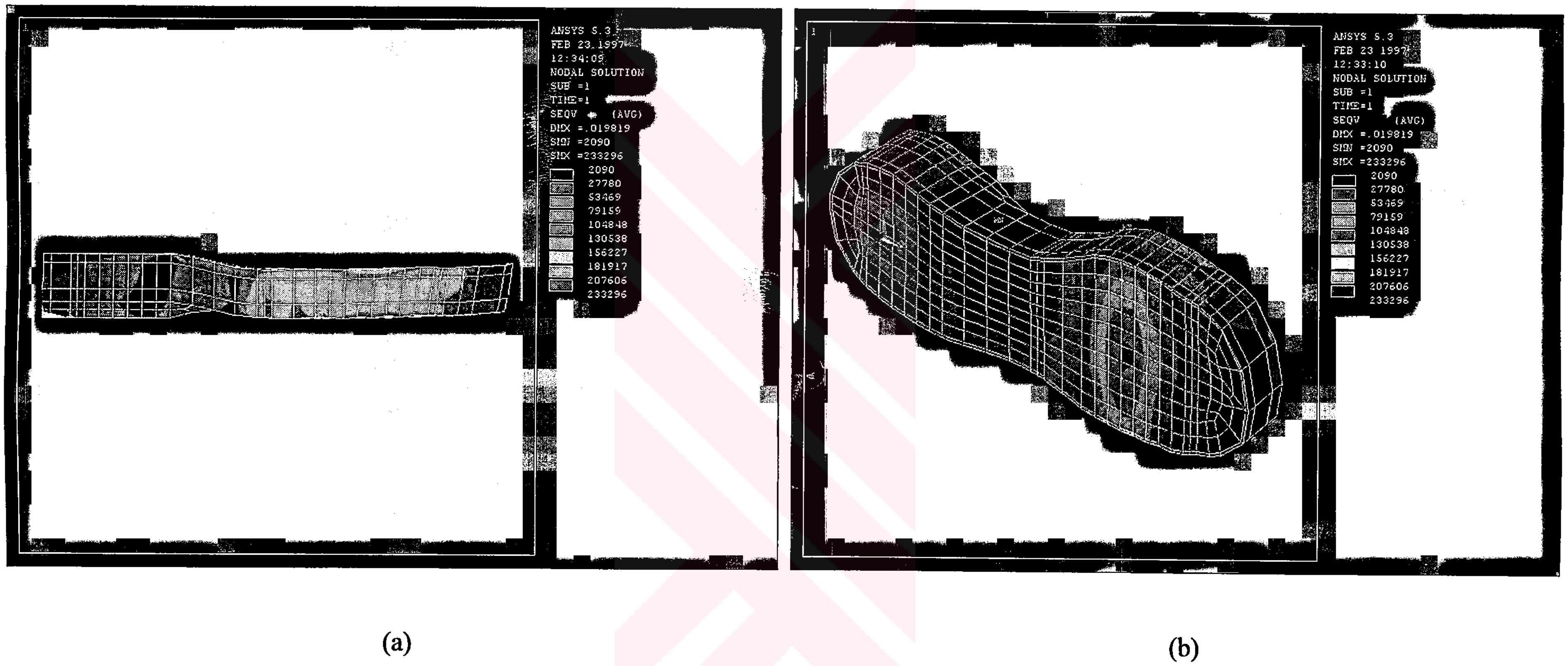
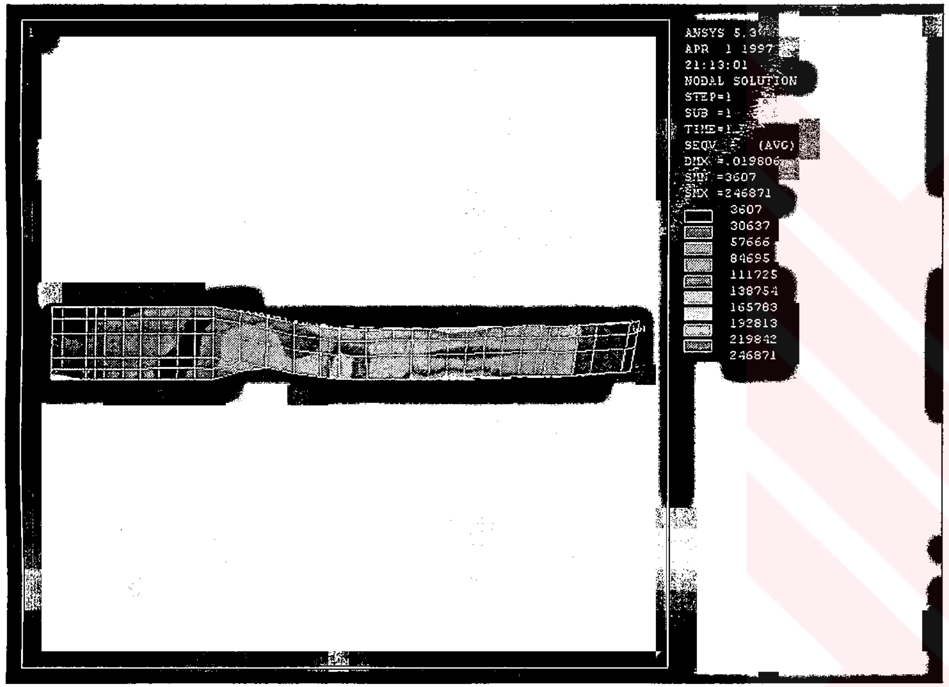
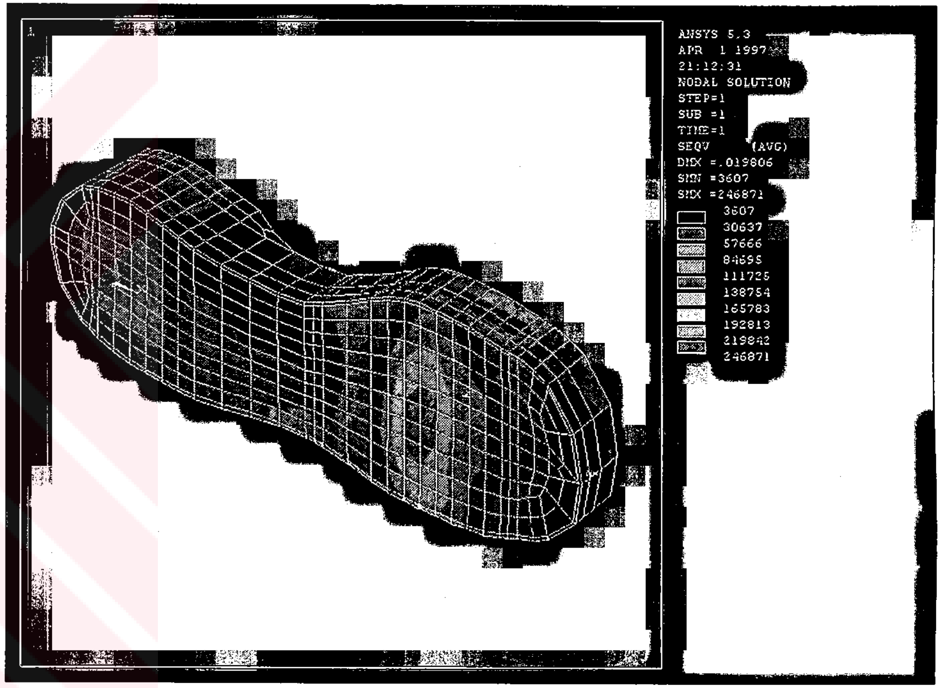


Figure 5.37 Equivalent Stress Distribution of the Sole (Upper sole: Polyurethane, Midsole: SBR, Heel and Lower Sole: Thermoplastic Rubber) After Optimisation with Objective Function of Total Strain Energy (a) Bottom view, (b) Isometric view

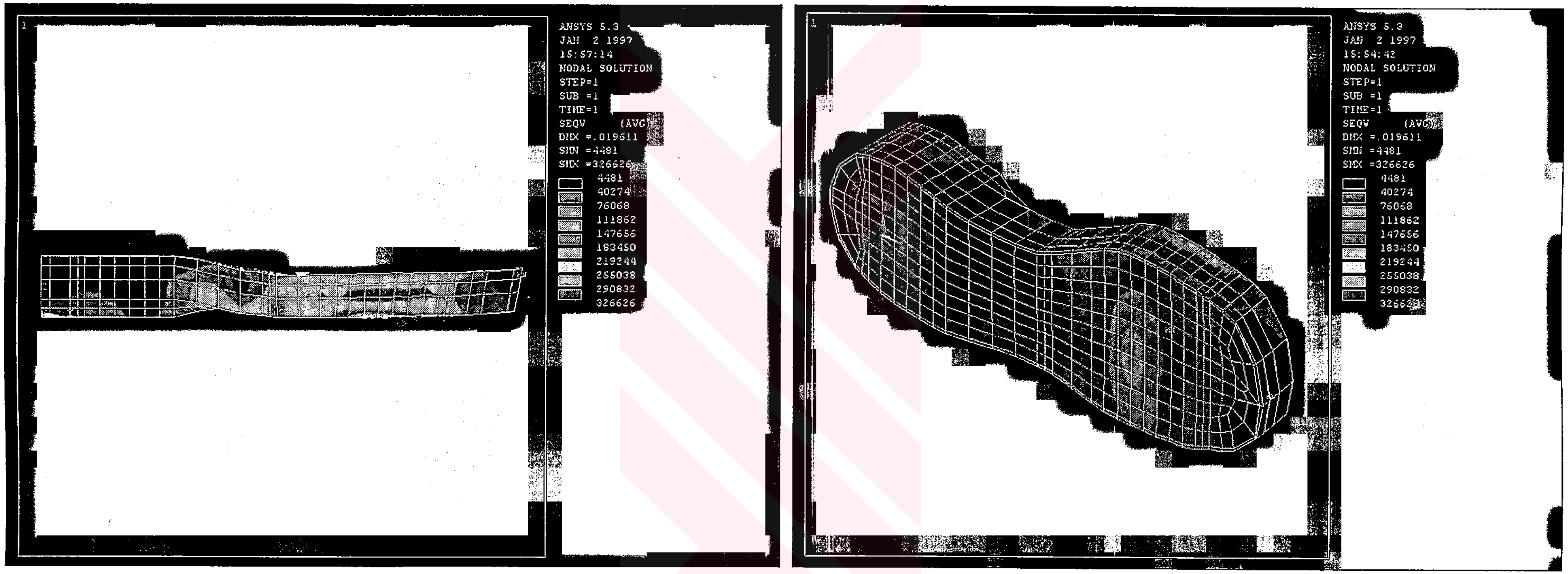


(a)



(b)

Figure 5.38 Equivalent Stress Distribution of the Sole (Upper sole: Polyurethane, Midsole: SBR, Heel and Lower Sole: Natural Rubber) After Optimisation with Objective Function of Total Strain Energy (a) Bottom view, (b) Isometric view



(a) (b)

Figure 5.39 Equivalent Stress Distribution of the Sole (Upper sole: SBR, Midsole: Polyurethane, Heel and Lower Sole: PVC) After Optimisation with Objective Function of Total Strain Energy (a) Bottom view, (b) Isometric view

CHAPTER VI

RESULTS AND DISCUSSIONS

6.1 INTRODUCTION

A model has been developed for a soldier boot and a number of runs have been carried out for various material and material combination in ANSYS. Most of the materials used by shoe manufacturers are involved in analysis. Some material properties are taken from handbooks and some of them are tested in which their samples are obtained from manufacturers. The properties of some materials are given in Appendix A. Furthermore optimisation process has been applied to initial results of analysis. This process has been carried out based upon the minimisation of the volume and minimisation of strain energy of sole under some design variables given in Chapter 5. For these cases, stress distribution of sole has been given.

6.2 RESULTS

In the analysis, 70 kg load is distributed over the sole into three regions. The sole is established on a rigid base, which is called ground, and its material property is selected too high from the Young's module of sole material. The rigid base (ground) is fixed in all directions to prevent its movement. Friction is defined between sole and ground. The analysis is carried out with large deformation module. So, the problem is analysed with boundary and geometrical non-linearities. At the end of each analysis stress distribution of each sole are taken graphically. The results are demonstrated in Figure 5.4-5.15. Table 6.1 represents the stress values taken from the graphics under the loading. Table 6.2 represents the displacement values obtained from the initial results. The analysis is carried out for different material types and its initial stress values are tabulated in same tables before.

An optimisation module is involved for the sole thickness. The optimisation is carried out with two objective functions; total volume and system strain energy. At the end of optimisation, optimum thickness values of the different soles are tabulated in Table-6.3 and Table-6.4. Stress distribution of some materials after optimisation is shown in Figure (5.16-5.39) and its maximum Von Misses stress values are tabulated in Table-6.5-6.6.

6.3 DISCUSSION

In ANSYS contact analysis requires a contact stiffness to obtain a converged solution. This stiffness value was found as 3MPa for all materials used in this thesis. It gives stable results. The small changes in the value of contact stiffness do not affect the results. Materials with 0.499 Poisson's coefficient gives smaller stress than materials with 0.49 Poisson's coefficient with the same young's modulus.

In the optimisation process, the optimum value is obtained when one of the design variables reaches its upper or lower limits. After the optimisation with total volume minimisation, the thickness values change from 26.705mm to 28.244mm for various material types. But the optimisation with minimisation of total strain energy, the thickness values change from 26.727mm to 34.301mm for various material types

Maximum stress values vary from 1.27% to 18.06% for different materials from its initial values. If the different sole materials are used for each layer, the change in thickness values are nearly zero. But stress values variation in first set of combination of materials is about 4.96% and it is 4.16% for the second set of combination of materials.

The results indicate that chloropene pur gum and hard rubber have got lower strength than the other material types. So, the sole layer material sets are chosen from the other materials for the multi-layer model with different materials. After optimisation with total volume objective function, volumes and thickness values which are obtained from these sets are nearly same, but the third set of sole materials (upper sole: Polyurethane, midsole: SBR, lower sole: Natural Rubber) give the lowest stress value.

Table 6.1. Initial Stress Values for Different Material Types

Material Name	Max .Von Misses Stress (MPa)	Elastic Modulus, E (MPa)	Poissons's Ratio
Natural Rubber	0.28342	6.1718	0.499
SBR	0.23655	5.1230	0.499
Chloropene Pur Gum	0.16425	3.1500	0.499
PVC	0.38495	8.5400	0.490
Chloropene Vul Cost	0.32101	5.0000	0.490
Poured Polyurethane	0.28003	4.4240	0.490
Thermoplastic Rubber	0.27720	3.7625	0.490
Hard Rubber	0.21848	3.0000	0.490
Different Material-1*	0.29815	-	-
Different Material-2**	0.35924	-	-
Different Material-3***	0.27290	-	-
Different Material-4****	0.35650	-	-

*Upper Sole: Polyurethane, Midsole: Natural Rubber, Lower Sole: PVC

**Upper Sole: Polyurethane, Midsole: SBR, Lower Sole: Thermoplastic Rubber

***Upper Sole: Polyurethane, Midsole: SBR, Lower Sole: Natural Rubber

****Upper Sole: SBR, Midsole: Polyurethane, Lower Sole: PVC

Table 6.2. Displacement values of the initial Results

Material Name	Displacement at X direction (m)		Displacement at Y direction (m)		Displacement at Z direction (m)	
	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
Natural Rubber	0.005701	-0.001459	0.000540	-0.000770	0.001300	-0.01855
Hard Rubber	0.005852	-0.001861	0.001006	-0.001353	0.000825	-0.019418
Chloropene Pur Gum	0.006053	-0.001766	0.000847	-0.001398	0.000805	-0.019457
Chloropene Vul Cost	0.005848	-0.001471	0.000716	-0.000925	0.001174	-0.018821
PVC	0.005387	-0.001509	0.000587	-0.000660	0.001558	-0.018019
SBR	0.005851	-0.001471	0.000718	-0.000926	0.001173	-0.018828
Thermoplastic Rubber	0.006004	-0.001538	0.000917	-0.001107	0.000945	-0.019106
Poured Polyurethane	0.00597	-0.001494	0.000800	-0.001095	0.001041	-0.018962

Table 6.3. Thickness Values of the Sole Optimised with Minimisation of Total Volume

Material Name	Optimum Thickness Values (mm)				Optimum Total Volume ($\times10^{-3} m^3$) **
	t_1*	t_2*	t_3*	t_4*	
Natural Rubber	26.727	16.601	13.549	8.3285	0.84801
SBR	26.727	16.601	13.549	8.3285	0.84801
Chloropene Pur Gum	28.244	19.947	12.422	6.6036	0.88129
PVC	26.727	16.601	13.549	8.3285	0.84796
Chloropene Vul Cost	26.727	16.601	13.549	8.3285	0.84791
Poured Polyurethane	26.727	16.601	13.549	8.3285	0.84789
Thermoplastic Rubber	26.705	16.601	13.549	8.3285	0.84724
Hard Rubber	28.244	19.947	12.422	6.6036	0.88077
Different Material-1***	26.727	16.601	13.549	8.3285	0.84790
Different Material-2****	26.727	16.601	13.549	8.3285	0.84797
Different Material-3*****	26.727	16.601	13.549	8.3285	0.84802
Different Material-4******	26.727	16.601	13.549	8.3285	0.84793

*Initial value of t_1, t_2, t_3, and t_4 are 30, 20,15,10 respectively

**Initial volume is $0.95027\times10^{-3} m^3$

***Upper Sole: Polyurethane, Midsole: Natural Rubber, Lower Sole: PVC

****Upper Sole: Polyurethane, Midsole: SBR, Lower Sole: Thermoplastic Rubber

*****Upper Sole: Polyurethane, Midsole: SBR, Lower Sole: Natural Rubber

******Upper Sole: SBR, Midsole: Polyurethane, Lower Sole: PVC

Table 6.4. Thickness Values of the Sole Optimised with Total Strain Energy

Material Name	Optimum Thickness Values (mm)				Total Strain Energy	
	t_1*	t_2*	t_3*	t_4*	Initial	Optimum
Natural Rubber	28.244	19.947	12.422	6.6036	22.895	22.596
SBR	32.054	15.877	10.431	6.4498	26.371	25.630
Chloropene Pur Gum	30.568	19.987	14.971	9.9942	37.996	37.956
PVC	26.727	16.601	13.549	8.3285	18.782	18.561
Chloropene Vul Cost	32.379	15.350	10.431	6.4498	26.280	25.652
Poured Polyurethane	34.301	15.546	11.343	9.2170	28.673	28.030
Thermoplastic Rubber	28.244	19.947	12.422	6.6036	32.152	30.705
Hard Rubber	32.379	15.350	10.431	6.4498	37.932	35.620
Different Material-1**	32.379	15.350	10.431	6.4498	29.406	28.076
Different Material-2***	28.244	19.947	12.422	6.6036	22.284	21.724
Different Material-3****	28.244	19.947	12.422	6.6036	25.264	24.640
Different Material-4*****	28.836	19.791	12.087	6.8328	23.382	22.694

*Initial value of t_1, t_2, t_3, and t_4 are 30, 20,15,10 respectively

**Upper Sole: Polyurethane, Midsole: Natural Rubber, Lower Sole: PVC

***Upper Sole: Polyurethane, Midsole: SBR, Lower Sole: Thermoplastic Rubber

****Upper Sole: Polyurethane, Midsole: SBR, Lower Sole: Natural Rubber

*****Upper Sole: SBR, Midsole: Polyurethane, Lower Sole: PVC

Table 6.5. Stress Values of the Sole Optimised with Minimisation of Total Volume

Material Name	Initial	Optimum	Material Properties	
	Max .Von Misses Stress (MPa)	Maximum Von Misses Stress (MPa)	Elastic Modulus, E (MPa)	Poisson's Ratio
Natural Rubber	0.28342	0.27719	6.1718	0.499
SBR	0.23655	0.22984	5.1230	0.499
Chloropene Pur Gum	0.16425	0.16040	3.1500	0.499
PVC	0.38495	0.38985	8.5400	0.490
Chloropene Vul Cost	0.32101	0.31120	5.0000	0.490
Poured Polyurethane	0.28003	0.29130	4.4240	0.490
Thermoplastic Rubber	0.27720	0.24727	3.7625	0.490
Hard Rubber	0.21848	0.17902	3.0000	0.490
Different Material-1*	0.29815	0.28334	-	-
Different Material-2**	0.35924	0.34429	-	-
Different Material-3***	0.27290	0.26322	-	-
Different Material-4****	0.35650	0.33924	-	-

*Upper Sole: Polyurethane, Midsole: Natural Rubber, Lower Sole: PVC

**Upper Sole: Polyurethane, Midsole: SBR, Lower Sole: Thermoplastic Rubber

***Upper Sole: Polyurethane, Midsole: SBR, Lower Sole: Natural Rubber

****Upper Sole: SBR, Midsole: Polyurethane, Lower Sole: PVC

Table 6.6. Stress Values of the Sole Optimised with Minimisation of Total Strain Energy

Material Name	Initial	Optimum	Material Properties	
	Max .Von Misses Stress (MPa)	Maximum Von Misses Stress (MPa)	Elastic Modulus, E (MPa)	Poisson's Ratio
Natural Rubber	0.28342	0.26838	6.1718	0.499
SBR	0.23655	0.24380	5.1230	0.499
Chloropene Pur Gum	0.16425	0.16806	3.1500	0.499
PVC	0.38495	0.38985	8.5400	0.490
Chloropene Vul Cost	0.32101	0.25220	5.0000	0.490
Poured Polyurethane	0.28003	0.27616	4.4240	0.490
Thermoplastic Rubber	0.27720	0.22185	3.7625	0.490
Hard Rubber	0.21848	0.19716	3.0000	0.490
Different Material-1*	0.29815	0.23330	-	-
Different Material-2**	0.35924	0.32959	-	-
Different Material-3***	0.27290	0.24687	-	-
Different Material-4****	0.35650	0.32663	-	-

*Upper Sole: Polyurethane, Midsole: Natural Rubber, Lower Sole: PVC

**Upper Sole: Polyurethane, Midsole: SBR, Lower Sole: Thermoplastic Rubber

***Upper Sole: Polyurethane, Midsole: SBR, Lower Sole: Natural Rubber

****Upper Sole: SBR, Midsole: Polyurethane, Lower Sole: PVC

CHAPTER VII

CONCLUSIONS

The evaluation of the results donates us the following conclusions:

- The developed sole model is flexible enough for the further studies due to independent thickness definition and separate model construction for the lower and upper parts of boot.

- The optimisation process provides a reasonable idea about the sole thickness for the given static load and design variable limits for various materials.

- For the given design variables, the optimal volume and stress distribution were obtained based on minimisation of total volume and strain energy respectively.

- The analysis gives a useful guide about sole material behaviour. A correlation between stress values, thicknesses and material properties has been described. This correlation suggests that the material with 0.499 Poisson's ratio should be used in multi-layer sole model as bottom layer. A material with higher Elastic Modulus improves the results when it combines with 0.499 Poisson's ratio.

- Volume minimisation gives a useful guide for the model made of one material but the weight will be a better design variable for the multi-layer model with different material. This should be considered in a further study.

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APPENDIX A

MECHANICAL PROPERTIES OF SOME RUBBERS USED IN THE ANALYSIS

Natural Rubber:

Young Module = $6.1718 * 10^6$ Pa

Yield Stress = $6.5 * 10^6$ Pa

Poisson Ratio = 0.499

Hard Rubber:

Density = 1170 kg/m^3

Young Module = $3.0 * 10^6$ Pa

Yield Stress = $3.2 * 10^6$ Pa

Poisson Ratio = 0.49

Poly (Chloroprene) Pur-Gum Vulcanizate [1]:

Density = 1320 kg/m^3

Young Modulus = $5.0 * 10^6$ Pa

Yield Stress = $3.15 * 10^6$ Pa

Poisson Ratio = 0.499

Poly (Chloroprene) Vulcanizate Cont. 33 % [1]:

Carbon Black (= 50 phr)

Density = 1420 kg/m^3

Young Module = $5.0 * 10^6$ Pa

Yield Stress = $5.5 * 10^6$ Pa

Poisson Ratio = 0,49

Polyvinyl Chloride (PVC):

Young Module = $8.54*10^6$ Pa

Yield Stress = $9.25*10^6$ Pa

Poisson Ratio = 0.49

Styrene Butadiene Rubber (SBR):

Young Module = $4.9785*10^6$ Pa

Yield Stress = $5.123*10^6$ Pa

Poisson Ratio = 0.499

Thermoplastic Rubber (TR):

Young Module = $3.7625*10^6$ Pa

Yield Stress = $4.25*10^6$ Pa

Poisson Ratio = 0.49

Poured Polyurethane:

Young Module = $4.424*10^6$ Pa

Yield Stress = $4.5*10^6$ Pa

Poisson Ratio = 0.49

APPENDIX B

A SAMPLE TEST RESULT OF PVC SOLE

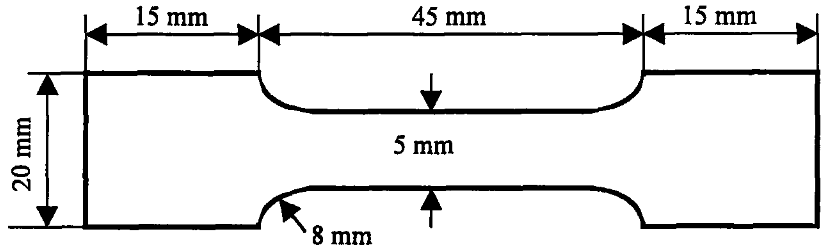

Figure B-1 Tested Specimen Dimensions (thickness is 5 mm)

Gaziantep University
Mechanical Engineering Department
Gaziantep

PVC

Test type: Tensile

Operator name: AHMET ERKLIG

Sample Identification: PVC-1
Interface Type: 42/43/4400 Series□□□
Machine Parameters of test:
Sample Rate (pts/s): 10.000
Crosshead Speed (mm/min □ □): 5.0000

Instron Corporation
Series IX Automated Materials Testing System 1.34
Test Date: 06 Nov 1998

Sample Type: ASTM

Humidity (%): 60
Temperature (deg. C): 18

Dimensions:

	Spec. 1	Spec. 2	Spec. 3
Width □ □ □ □ (mm □ □ □ □)	4.7000	4.7000	4.7000
Thickness □ □ (mm □ □ □ □)	4.9000	5.0000	5.0000
Spec gauge len (mm □ □ □ □)	45.000	45.000	45.000
Grip distance (mm □ □ □ □)	100.00	100.00	100.00

Out of 3 specimens, 0 excluded.

Specimen Number	Displcment at Peak (mm)	% Strain at Peak (%)	Load at Peak (kN)	Stress at Peak (MPa)	Displcment at Break (mm)	% Strain at Break (%)	Load at Break (kN)	Stress at Break (MPa)	Load at 0.2% Yield (kN)
1	83.34	185.2	.2088	9.066	84.50	187.8	.2028	8.806	.0174
2	64.42	143.1	.1973	8.396	65.29	145.1	.1808	7.694	.0580
3	62.00	137.8	.1409	5.996	62.93	139.8	.1306	5.557	.0531
Mean:	69.92	155.4	.1823	7.819	70.90	157.6	.1714	7.352	.0428
Standard									

Deviation:	11.69	26.0	.0363	1.614	11.83	26.3	.0370	1.651	.0222
Mean - 2.00 * Sdv:	46.54	103.4	.1097	4.590	47.24	105.0	.0974	4.051	*****
Mean + 2.00 * Sdv:	93.29	207.3	.2550	*****	94.57	210.2	.2454	*****	.0871
Minimum:	62.00	137.8	.1409	5.996	62.93	139.8	.1306	5.557	.0174
Maximum:	83.34	185.2	.2088	9.066	84.50	187.8	.2028	8.806	.0580
CofOfVar:	16.72	16.72	19.93	20.65	16.69	16.69	21.59	22.45	51.72

Specimen Number	Stress at 0.2% Yield (MPa)	Young's Modulus (MPa)	LASE 1% (kN)	LASE 2% (kN)	EASL .5 KN (%)	EASL 2.5 KN (%)	Energy to Break Point (J)	Tensile Energy Absorption (N/mm)
1	8.7559	8.435	.0038	.0042	----------	----------	10.160	48.02
2	9.4690	10.500	.0108	.0124	----------	----------	8.021	37.93
3	7.2580	6.685	.0025	.0039	----------	----------	5.120	24.21
Mean:	1.8280	8.540	.0057	.0068	----------	----------	7.766	36.72
Standard Deviation:	.9341	1.910	.0045	.0048	----------	----------	2.528	11.95
Mean - 2.00 * Sdv:	-.0405	4.720	*****	*****	----------	----------	2.710	12.81
Mean + 2.00 * Sdv:	3.6960	12.360	.0147	.0164	----------	----------	12.820	60.62
Minimum:	.7559	6.685	.0025	.0039	----------	----------	5.120	24.21
Maximum:	2.4690	10.500	.0108	.0124	----------	----------	10.160	48.02
CofOfVar:	51.11	22.36	78.67	70.28	----------	----------	32.55	32.55