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FACULTY OF ENGINEERING

THE IMPACT OF APPLICATION OF A NUMERICALLY CONTROLLED PLATE FORMING MACHINE ON SHIPYARD PRODUCTION

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INTRODUCTION

In the last few years, the definition of the hull shape in a mathematical form was achieved in several establishments all over the world. As a result, it became possible in the design office to define any part of the hull mathematically and therefore very accurately. In order to make use of this achievement, numerically controlled machine tools, for the production of the different parts of the ship hull, have been the subject of much research work in the U.K., U.S.A., and in Norway. The first achievement in this field was the numerically controlled flame cutters which are developed to a satisfactory degree of operation and are now in use in different shipyards (1). These machines have proved their superiority to the conventional type flame cutters. The accuracy is claimed to be better than ± 1/8 inch over 40 ft. plate length. The machine burns the different plate shapes from basic dimensional information prepared in the design office and stored on a punched or a magnetic tape.

The second application of the numerical control technique was to the frame bending machine. The design of this machine has been studied in Britain (2), in U.S.A. (3) and in Norway (4). As a result of the research work carried out by the author on the design of this machine, a numerically controlled frame bending machine is now being built and it is anticipated that it will start production in 1968. This machine could bend ship frames from basic dimensional information prepared on a punched tape.

The impact of using these two machines on control of shipyard production, planning and economy will be much improved when plate forming operations are also controlled numerically. This will eliminate completely the mould loft and the use of templates in addition to dispensing with the skill required for these operations.However, the largest savings are likely to accrue from increased accuracy of individual parts which will reduce assembly times and rectification costs. Consequently, the forming of ship plates, although a minor operation by itself, constitutes a major operation having regard to the capital expenditure tied up for it, skilled labour involved, the impact of its application on the other numerically controlled machine tools, subsequent rectification due to inaccuracies and the planning and the control of production of the steel shop.

The main objective of this work is to investigate whether it is necessary to design and develop a numerically controlled plate forming machine or not. The argument is based on different factors, mainly, the impact of application of computers to the shipbuilding industry, the impact of application of plate forming machines on the flow line production, the number of plates required to be bent to two dimensions and to three dimensions, the utilisation factor of the machine, the accuracy required during the plate forming operation and its impact on the size of the shipyard and the number of berths. The feasibility of designing this machine, mechanically and economically, are also discussed and some forming techniques are proposed and several lines of future research are suggested. Further, the mechanics of plate forming is investigated with particular reference to curvature distribution over the plate surface, stress distribution across the plate thickess. . . etc. In addition, the two main problems associated with cold bending namely, spring back and buckling are examined. It is shown that further analysis and experimentation are required in order to have deep understanding of the mechanics of three dimensional plate forming.

It is concluded that the forming of ship plates has a great effect on the economic advantages of using the electronic computer for production, planning and control of the shipyard. It is also concluded that these plates should be produced econmically, accurately and under control in order to get all the benefits of a fully integrated numerically controlled system controlled by the design office of the shipyard.

METHODS OF PLATE FORMING

Ship plates can be divided into three categories, namely, flat plates, plates bent to single curvature and plates bent into double curvature. The production of the first type of these plates is indirectly achieved since all plates going to the production line should pass through a straightening machine. Single curvature plates are normally produced by plate bending rolls. The workman depends on his experience to determine the relative positions of the rolls so that when the plate is bent, it may attain the desired shape after spring back. Double curvature plates are produced by different methods depending on the shipyard practice. However, the number of these plates is relatively small in comparison with the total number of the ship hull plates, about 10—20 plates depending on the ship type. These plates normally exist in the stern region as well as in the bow region. Bulbous bows are examples of the most complicated and expensive three dimensional shape to be produced. The forming of these three dimensional plates is carried out either in the hot state or in the cold state, as follows :—

a) *Hot forming of ship plates* (5) :

The plate is heated in a furnace to the red hot state, (repeated heating may be necessary before the plate is formed to the required shape). Although this method of plate forming eliminates the problem of spring back, it involves a large area and capital expenditure (the furnace is not always used to full capacity) as well as it involves difficult working conditions. The material may be overheated and this may have a deleterious effect on the quality of the steel. Readjustments are necessary after cooling to correct the change in shape due to contractions and distortions.

b) *Cold forming of ship plates* :

Cold forming methods have replaced the previous method for forming ship plates. Depending on whether forming is required to single curvature or double curvature, different methds of cold forming are in common use in shipyards. These methods are summarised as follows :

1. *Forming of ship plates to single curvature.*

Ship plates required to be formed to single curvature, such as those in the vicinity of the bilge, are normally shaped by bending rolls, or by press brakes. Although plates formed by this method will have curvature in one direction only, double curvature could be achieved by packing thin metal or wooden strips at some positions along the bending rolls.

2. *Forming of ship plates to double curvature.*

This method of forming is always confronted with two main problems, namely spring back and distortions of the plate due to buckling, In order to overcome these two problems, different methods of three dimensional forming are used. These methods are summarised as follows :

i) *Three-dimensional die* :

Although the die shape takes into account the effect of spring back (only empirical rules are used for spring back calculations), the final plate shape normally requires further adjustments.

ii) *Forming of ship plates using the corresponding frame rig* :

Some shipyards form the plates by pulling them onto the frames. This method is only possible when relatively thin plates and small curvatures are required. The plate may not be cut to the proper size before pulling onto the frames and subsequent trimming off the excess material is inevitable and is normally carried out by manual flame cutting.

iii) *Forming of ship plates using a telescopic rig* :

Some shipyards have a telescopic rig whereby a three dimensional shape could be obtained by adjusting the height of each telescopic rod (which is calculated beforehand). The plate is then placed in position and welded to get the final plate shape, see fig. (1).

iv) *Hot line forming of ship plates.*

In Japan and Sweden, some shipyards form their plates by a technique called (hot line forming). The plate is heated by a torch along certain contours and at the same time cold water is splashed on the plate. This heating and cooling will induce a system of internal stresses which will distort the flat plate. However, this method is based on art rather than science, i.e. is not fully developed scientifically. No figures are available regarding the accuracy of forming (6).

It should be noted that there are two other techniques used for three dimensional forming of plates. The first, is called stretch forming and is widely used in aircraft industry. The second, is high rate forming or explosion forming which is used for forming small complicated three dimensional shapes. However, none of these two techniques have been used for forming ship plates and it is believed that they will not be used since the forming forces and the plates dimensions will hinder their practical application for forming ship plates.

In all the previous methods of plate forming, the shape is checked by templates (normally wooden templates) which are prepared in the mould loft (full scale or 1/10th scale). However, some of these templates are prepared from the shapes of the frames in the stem and stern areas, where double curvature is inevitable.

It should be realised that the whole operation relies on the skilled labour and that there is no absolute measure for the accuracy of forming.

In order to obviate the need to three dimensional forming with its associated problems, some research has been carried out to investigate the possibility of producing a ship which does not experience any curvature in any part of its hull, i.e. straight framed ships(7). It was shown that it is possible to construct such a ship which gives a reasonable performance in calm water when knuckle lines follow the stream lines. However, for the ship motion among waves, it was shown that there is an increase in resistance to motion. The increased running costs resulting from increased resistance is believed to be higher than the production costs of the double curved plates.

SOME IDEAS FOR NUMERICAL CONTROL OF PLATE FORMING

It is believed that none of the techniques mentioned before could have feasible and direct practical application for the design of a numerically controlled plate forming machine. The following are the suggested techniques which are believed to be the most suitable methods for the development of such a machine, after being developed to a satisfactory degree of application :-

1. Hot line forming
2. Press forming using an infinitely variable die
3. Squeeze forming

In hot line forming, the heating source could be made to move on certain prescribed contours calculated in advance in such a way that a certain system of internal stresses is imposed in the plate material.

This internal stress system will be such that the plate will "distort" or formed to the required shape. It is possible that the numerically controlled flame cutting machine could be used for this purpose.

In the case of press forming, a suitable die is required to withstand the high forming forces. The shape of the die should take spring back effect into consideration. It should be realised that it would be very expensive and uneconomical to form a die to suit each curved plate. This problem, however, could be solved by designing an infinitely variable die which could be controlled to take any required shape. The design of such a die could be based on the idea of the telescopic rig shown in Fig. (1), or on the method of forming shapes for some rocket parts as given in reference (10). In Fig. (1), the height of each ordinate i.e. z is adjusted such that the equation to the surface given by $Z = f\ (x,y)$ is satisfied. This could be achieved in the z-x plane by the equation $Z = f\ (x)$ and in the z—y plane by the equation $Z = f\ (y)$. It is believed that it is feasible to design a matrix of screw or hydraulic jacks which are numerically controlled in the (z-x) and (z-y) planes.

In the case of squeeze forming, the required curved shape could be achieved by applying a very high concentrated force on a localised area. A system of internal stresses will be induced in the material in such a way that the plate should attain a certain amount of curvature. When the applied force is controlled and moves on certain calculated contours, ship plates could be numerically formed to double curvature. Poissons' ratio effect will induce orthogonal curvature which should be taken into account in the subsequent contours. The final shape of the plate is the resultant of the accumulative effect of each squeezing run. This will be clarified in the study of the mechanics of plate forming, as will be shown later.

This method of forming requires a numerically controlled measuring and checking system. Discrepencies with the required plate shape could be corrected by repeated squeezing on certain contours over the plate surface.

THE IMPACT OF USING A NUMERICALLY CONTROLLED PLATE FORMING MACHINE ON THE THE SEQUENCE OF OPERATIONS OF SHIP PLATES

The different plates must be brought to the workshop in the correct sequence. The different working operations are usually planned in such a way that bottlenecks are eliminated, idle time and handling operations are reduced to minimum; since about 60 to 80% of the working time in the plater's shop is spent in the handling and transport work (8). As plates comprise about 80—85% of the material weight of a vessel (9) (i. e. about 65% of the handling time), plates will be responsible for the greater part of the handling costs which should be made as low as possible.

Fig. (2) shows the probable sequence of operations of ship plates in a shipyard. It is assumed that only welded constructions are considered. It shows also that between 7-10 handling operations are required. However, this number of handling operations can be reduced by using automatic conveyors. Buffer areas are necessary at various stages to allow for the difference in speeds of the various machines and the necessary times for the different operations. Much time is lost in handling in and out of the buffer areas and therefore a considerable effort should be made to reduce these areas by matching the speeds of operations of all the machines so as to give a continuity of flow. The marking operations shown in Fig. (2) can be performed by using either full scale templates or by optical projection techniques.

Fig.(3) shows a proposed flow diagram of ship plates operations. It is shown that all the information controlling the production line is from the design office which performs the necessary calculations and supplies all the raquired data for machine tool control, marking .... etc. It is proposed that a single machine for plate straightening, shot-blasting and priming may be designed to perform simultaneously these operations. It is believed that the design of such a machine is not a formidable task Ship plates are usually divided into three major categories namely, plates having straight edges, plates having curved edges and miscellaneous plates. Each category has its own route in the poduction line, as shown in Fig.(3). It is also shown that single curvature plates are shaped on a bending roll (or by press brakes) while three dimensional plates are formed by any conventional method. For both machines, templates can be obtained from the numerically controlled frame bender. In this way, mould loft could be completely dispensed with. This proposed system could be considered as an intermediate stage between the traditional shipyard and the anticipated computer controlled shipyard.

Fig. (4) shows the introduction of a numerically controlled plate forming machine in the production line for executing all plate forming whether to single curvature or double curvature. In this case, no template whatsoever will be required for the production of any part of the ship. Also by introducing a numerically controlled marking, which is successfully used in some Scandinavian shipyards, for both flat and curved plates, the production line will be more compatible and could be fully controlled by the design office. The numerically controlled marking is achieved by projecting a cross of light on the steel plate at the required positions. A carriage carrying the projecting device moves transversely over a trolley which moves longitudinally over rails,see Fig. (5). The movements of both the trolley and the carriage are numerically controlled.

THE IMPACT OF USING A NUMERICALLY CONTROLLED PLATE FORMING MACHINE ON ECONOMY OF SHIPYARD PRODUCTION

The development of automatic machinery involves large capital costs and therefore their design and production should be justified economically and their utilization should be studied very carefully so that idle time could be made as low as possible. This can only be achieved by accurate planning and by investigating the interaction between the different machines in use and the impact of their application on the flow line production and the economy of the final product.

If the main shipyard operations, namely, flame cutting, frame bending, marking and plate forming can be done numerically, then all lofting, scrieve boards and templates can be completely eliminated. This would produce savings in material, space, labour, material for templates and savings resulting from increased accuracy.

The savings in labour are difficult to estimate. Although fewer men will be employed for operating the numerically controlled machines, planning, programming and data preparation may require more qualified people with higher salaries. The savings resulting from increased accuracy are impossible to forecast precisely, but a considerable saving in material is expected with a consequent reduction in scrap. Since computer controlled flame cutting machine has resulted in a savings of 5—10% in the amount of weld metal deposited (1), it will be expected that greater savings will be achieved in the case of plates, as the gap between the plates and the mating frames will be reduced considerably. However, it is in the reduction of rectification costs and fairing on the berth that the biggest savings should come.

The introduction of a numerically controlled plate forming machine will certainly save some handling operations and buffer areas. In addition, the efficiency of the machine will be much improved when a numerically controlled marking machine is also used.

The utilization factor of a numerically controlled plate forming machine, if it is used only for forming ship plates, will be very low. Unless the shipyard output is relatively high, this machine will make the forming of three dimensional plates a very expensive operation. However, it should be realised that our interest is in the final costs of the ship and not the individual costs of every operation. The savings through integrating all operations in the shipyard with the design office may be much higher than the increased costs of forming ship plates. In addition, this machine could be used for forming three dimensional plates for submarines, pressure vessels ... etc.

Further, it is to be noted that the size of the shipyard (determined either from the tonnage launched per year or from the number of ships launched annually) has a great effect on the economics of curved plate forming using a numerically controlled plate forming machine.

The foregoing is a brief review of all the expected benefits to be gained from introducing a numerically controlled plate forming machine in a shipyard. However, it should be realised that actual figures for the economic advantages of using this machine will only be available when such machine is actually working in one of the shipyards. At present there is not enough data from other numerically controlled machine tools that can be taken as a reference for their exact economic advatages, regarding capital cost, maintenance costs, rate of depreciation...etc.

Before investigating the mechanical and control side of the numerically controlled plate forming machine, it is necessary to study the mechanics of the plate forming process. This will certainly clarify some of the problems associated with the behaviour of the plate material during the forming operation.

ANALYSIS OF THE MECHANICS OF THREE DIMENSIONAL COLD BENDING OF SHIP PLATES

The problem of plate bending has been studied by several investigators as given in references (11), (12), (13) and (14). Their approach was based on some simplifying assumptions such as two dimensional bending (a cylinderical surface), ideal stress strain diagram, the plate dimensions are effectively small... etc.

In the case of ship plates which are formed to three dimensional shapes, none of these assumptions could be applied if a rigorous solution for the mechanics of plate forming is required. However, for the purpose of this paper, it is only necessary to give a qualitative analysis of the physical nature of the plate bending process. As a result, a brief analysis, based on the light of the previous investigations, will be given.

It is important to note that forming of ship plates into a curved shape necessitates bending it beyond its elastic limit, otherwise the plate will spring back to its original shape after releasing the bending forces. Therefore, the problems associated with the plate forming will be mainly the spring back, or elastic recovery, and buckling or warping of the plate before it attains the required shape. In order to investigate these problems, it is necessary to understand the behaviour of the plate material under loading in the elastic and plastic regions in terms of stress distribution, spring back, curvature distribution and buckling. For this purpose it is assumed that the stress-strain diagram is of the ideal plastic type as shown in Fig. (6). Strain hardening can be neglected on the assumption that plate dimensions are very large in comparison with the plate thickness and that bending is normally carried out to small curvatures.

1. *Stress Distribution Due to Forming*

The stress distribution across the plate thickness, taking into account the effect of radial stresses, was studied by Lubahn and Sachs(14), for two dimensional shapes. Although their analysis is based on an ideal stress-strain diagram, it gives a thorough investigation of the mechanics of plate bending into the plastic range, including the determination of the neutral surface position. The stress distribution considering non-linear strain hardening for a two dimensional surface is given in Appendix (I). The stress distribution across the plate thickness for three dimensional shapes under loading is the resultant of bending, shear and torsion stresses and is rather difficult to be accurately determined.

When the stress distribution across the plate thickness is investigated (14), it is assumed that the neutral surface does not experience any stress or strain. This assumption will only be valid when the in-plane forces of the plate are neglected. However, when three dimensional surfaces are considered, such as a ship plate in the stern region, the in-plane forming forces cannot be neglected. These additional in-plane stresses should be taken into account when investigating the stress distribution across the plate thickness.

2. *Spring Back*

The spring back problem of sheet metal has been studied before on the assumption that the true stress-strain diagram of the material is known (12),and(15). It was concluded that it is rather difficult to calculate precisely the amount of spring back which when taken into consideration will give the desired plate shape after the first trial. This is due to the variation in the stress-strain diagram for the different plates and even for the same plate at different locations. This variation in the mechanical properties explains the scatter in the experimental results of the spring back data which was found to form a band and not a definite relationship (2). The degree of scatter depends on the condition of the test specimen i.e. for annealed specimens the scatter was much less than for specimens in the as-delivered condition.

As far as ship plates are concerned, spring back represents a major problem confronting the design of a bending machine for forming three dimensional plates. In practice, spring back is overcome by either overbending the plate or by heating the plate to the red hot state. Overbending in the cold state may require several trials before the final shape is achieved. Heating is rather expensive and may have an adverse effect on the plate material as stated before.

It is concluded, therefore, that the only possible way to overcome spring back problems in a machine tool for forming ship plates is by providing the machine with a servo-mechanism which should hunt about the desired shape until it is finally achieved. The hunting process may be reduced to one or two hunting operations by supplying the servo-mechanism with sufficient spring back data obtained from several tests.

3. *Curvature Distribution Over the Plate Surface*

The curvature distribution over the plate surface can be obtained from the assumption that the strain distribution across the plate thickness is linear for both elastic and plactic bending and is given by :

$$\frac{1}{\varrho} = \frac{\epsilon}{z}$$

where ε = strain at a distance z from the neutral axis, see fig. (7)

$\frac{1}{\varrho}$ = curvature attained by the neutral axis.

In order to form a plate to double curvature, it must be acted upon by an external system of forces and moments. Consider the case shown in Fig. (8), the plate is subjected to two sets of moments, M_x and M_y which act in the planes $z - x$ and $z - y$ respectively.

The strains and curvatures resulting from the application of these moments are treated separately for the elastic and plastic regions of the stress-strain diagram of the material. It should be noted that it is necessaıy to study the behaviour of the plate material in the elastic range as it will help to understand the spring back problem.

a) *Elastic region*

The curvatures in the z-x and z-y planes due to M_x and M_y are given by :

$$\frac{1}{\varrho'_x} = \frac{1}{\varrho_x} - \frac{\mu}{\varrho_y}$$

and $$\frac{1}{\varrho'_y} = \frac{1}{\varrho_y} - \frac{\mu}{\varrho_x}$$

where : $\frac{1}{\varrho'_x}$ and $\frac{1}{\varrho'_y}$ are the curvatures attained by the plate when it is loaded in the elastic region. They can be calculated when the applied bending moments M_x and M_y or the material properties i.e. stress-strain diagram and Poisson's ratio (μ) are known (16).

b) *Plastic range*

In the plastic range, when the bending moments M_x and M_y are applied, the plate will attain the curvatures $\frac{1}{\varrho''_x}$ and $\frac{1}{\varrho''_y}$ in the z-x and z-y planes respectively. These curvatures are functions of M_x, M_y and plate thickness t_p i.e.

$$\frac{1}{\varrho''_x} = f\,(M_x,\ M_y,\ t_p)$$

and $$\frac{1}{\varrho''_y} = f\,(M_y;\ M_x,\ t_p)$$

However, M_x and M_y are functions of the plate dimensions and the stress strain relationship in the plastic range which is given by (14) :

$$\frac{d\sigma_1 - d\sigma_2}{d\varepsilon_1 - d\varepsilon_2} = \frac{d\sigma_2 - d\sigma_3}{d\varepsilon_2 - d\varepsilon_3} = \frac{d\sigma_1 - d\sigma_3}{d\varepsilon_1 - d\varepsilon_3}$$

where σ_1, σ_2 and σ_3 are the three principal stresses,

ε_1, ε_2 and ε_3 are the three principal strains.

Then the curvatures $\frac{1}{\varrho''_x}$ and $\frac{1}{\varrho''_y}$ can be calculated from the strain distribution under any system of loading using the above stress strain relationship and the constant volume equation as given by :

$$d\,\varepsilon_1 + d\,\varepsilon_2 + d\,\varepsilon_3 = 0$$

The permanent curvatures $\frac{1}{\varrho X}$ and $\frac{1}{\varrho Y}$ in the z-x and z-y planes can be calculated for any curved plate which could be represented mathematically by an equation of the form : $z = f(x, y)$ as follows :

$$\frac{1}{\varrho_X} = - \frac{\frac{\partial^2 z}{\partial x^2}}{\left[1+\left(\frac{\partial z}{\partial x}\right)^2\right]^{3/2}}$$

and
$$\frac{1}{\varrho_Y} = - \frac{\frac{\partial^2 z}{\partial y^2}}{\left[1+\left(\frac{\partial z}{\partial y}\right)^2\right]^{3/2}}$$

If the amount of spring back in curvature i.e. $\frac{1}{\varrho'_x}$, $\frac{1}{\varrho'_y}$ can be calculated at any point on the plate surface, the amount of curvature which should be imposed on the plate before spring back could be calculated as follows :

$$\frac{1}{\varrho''_x} = \frac{1}{\varrho_X} + \frac{1}{\varrho'_x}$$

and
$$\frac{1}{\varrho''_y} = \frac{1}{\varrho_Y} + \frac{1}{\varrho'_y}$$

In order to obtain correct values for $\frac{1}{\varrho''_x}$ and $\frac{1}{\varrho''_y}$ a large amount of data for spring back should be accumulated. This can only be achieved by running a series of tests on steel plates.

4. *Buckling of Ship Plates*

Buckling represents also a major problem confronting the forming of ship plates to double curvature. The stress system acting in the compression region in addition to the compressive in-plane stresses, which are induced by the forming process, as shown in Fig. (9), hinder the plate material to attain the desired shape without buckling at some points, (it is impossible to form the plate material under triaxial compressive stresses).

As was stated before, forming necessitates the material to be in the plastic range. If we neglect strain hardening, (i.e. assuming that the material behaves in a purely plastic, fashion, the stress condition at which yielding of the material takes place, without buckling, could be obtained by applying Tresca yield criterion which is given by :

$$\tau_m' = \frac{\sigma_\theta - \sigma_\psi}{2} = \pm \frac{\sigma_y}{2} \qquad \text{.. (a)}$$

$$\text{or} \qquad = \frac{\sigma_\theta - \sigma_r}{2} = \pm \frac{\sigma_y}{2} \qquad \text{.. (b)}$$

$$\text{or} \qquad = \frac{\sigma_\psi - \sigma_r}{2} = \pm \frac{\sigma_y}{2} \qquad \text{.. (c)}$$

i.e. yielding of the material was assumed to start when maximum shearing stresses reach the yield limit in simple shear (16).

where σ_y = yield stress of the material.

τ_m = maximum shear stress of the material.

σ_r = radial compressive stress.

σ_θ = tangential stress in the z-x plane.

σ_ψ = tangential stress in the z-y plane.

σ_r, σ_θ, σ_ψ are the three principal stresses.

As buckling is considered, σ_θ and σ_r will always be compressive whereas σ_ψ may be tensile or compressive. Since σ_r is relatively small, in comparison with σ_θ and σ_ψ, the conditions of yielding can be simplified to :-

$$\sigma_\theta - \sigma_\psi = \sigma_y \qquad \text{.. (d)}$$

$$\text{or} \quad \sigma_\theta - \sigma_r = \sigma y \qquad .. \quad (e)$$

Therefore, in order to form the plate to the required three dimensional shape without buckling, the magnitude of $| \sigma_\theta - \sigma_\psi |$ and/or $| \sigma_\theta - \sigma_r |$ must be at least equal to the yield stress of the material. This could be achieved by either increasing σ_θ and/or σ_ψ, or by reducing σ_r. Since σ_r is dependent on σ_θ, the practical solution, for three dimensional forming, could be obtained by reducing σ_ψ or increasing σ_θ without affecting σ_r. This is achieved in aircraft industry by stretch forming.

From the previous analysis, it is realised that any theoretical solution will only help understanding the behaviour of the plate material during forming. Some tests may be required to throw the light on the actual behaviour of these plates and also to correlate theoretical analysis with experimental work. From the auther's experience in the design of a numerically controlled frame bending machine, it is believed that full understanding of the mechanics of forming will also help in the design of the control and measuring systems.

Further, it is expected that using the technique of hot line forming requires a thorough investigation of the distortions resulting from the application of a localised source of heat on mild steel plates. In the case of high rate forming the behaviour of the material under impact loading or high rate loading should be investigated carefully with particular reference to its effect on the ductility and the variation in thickness of the plate.

CONCLUSIONS

At this stage, it is rather difficult to state that it is technically possible to design a numerically controlled plate forming machine. However, the economic advantages which will be realised subsequent to desingning such a machine may justify all the research and development work necessary for the production of a numerically controlled plate forming machine. A shipyard performing all operations using numerically controlled machine tools will be fully controlled by the design office (or planning department) in such a way that advance planning and scheduling could be efficiently realised.

It may also be concluded that although the cost of forming ship plates may increase, the total cost of the ship may be reduced. This will also be realised when the utilisation factor of the machine is increased by using the machine for forming three dimensional plates for other fields of industry such as pressure vessels ... etc.

It is suggested that an accuracy of $\pm$ 0.1 cm. over a span of 1.0 m should be the aim in the design of a numerically controlled plate forming machine. This accuracy will result in a big saving in erection times and costs as well as in the amount of weld metal deposited which, in turn, will result in a reduced distortion.

FUTURE WORK

From the literature on Numerical Control Techniques (18), it is shown that a tremendous amount of work has been done in this field. It is also shown that the application of this technique is so far efficient and economical in several fields. In order to make the design of a numerically controlled plate forming machine a practical and economical solution, few lines of research are suggested as follows :

1. Developing the different techniques whih can be used for forming ship plates.

2. Investigating the mechanics of three dimensional forming with particular perference to spring back and buckling.

3. Designing an infinitely variable die.

4. Running a series of tests on ship plates for collecting data on the two problems of spring back and buckling.

5. Developing a measuring system to be used for the numerical control of the forming machine.

6. Developing a servo-mechanism to work in conjuction with the measuring system in order to overcome the spring back.

7. Developing a computer programme for mathematically defining each curved plate and also each contour of every plate.

8. Investigating the possibility of forming high tensile steel plates.

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APPENDIX I

Bending Moment — Curvature Relationship.

It is assumed that the stress-strain diagram can be represented by an exponential function, such as :

$$\sigma = \sigma_0 \, \epsilon^{\frac{1}{n}}$$

This fuction assumes nolinear strain hardening (19), see Fig. (10)

where σ = stress

ϵ = strain

σ_0, n = constants

It was found that for mild steel having a yield stress of about 16.0 tons per sq. inch and an ultimate stress of about 28 ton/sq. inch, the values of σ_0 and n are approximately 35.9 and 9.0 respectively. Therefore, the σ — ϵ relationship becomes :

$$\sigma = 35.9 \, \epsilon^{0.111}$$

Assuming that lines perpendicular to the neutral surface remain perpendicular i. e.

$$\epsilon = \frac{y}{\varrho}$$

where y = distance from the neutral axis

$1/\varrho$ = curvature attained by the neutral axis

The bending moment — curvature relationship is obtained as follows :

$$M = \int_{-t/2}^{+t/2} \sigma . \; y . \; dy$$

where M = Bending moment / unit length.

t = plate thickness

$$M = 2 \int_{0}^{t/2} \sigma_0 \left(\frac{y}{\varrho}\right)^{\frac{1}{n}} . \; y . \; dy$$

$$= \frac{n \; K}{2n+1} \left[t^{\frac{2n+1}{n}} \right]$$

where $$k = \frac{2 \; \sigma_0}{\varrho^{\frac{1}{n}}}$$

Where $n = 9.0$ and $\sigma_0 = 35.9$, as shown before.

$$\therefore \; M = 33.95 \; t^2 \; \epsilon^{0.111}$$

or $$M = 33.95 \; t^{2.111} \left(\frac{1}{\varrho}\right)^{0.111}$$

The bending moment — Curvature relationship is represented by Fig. (12).

The stress distribution across the plate thickness is shown in fig. (11) and is given by :—

$$\sigma = \sigma_0 \left(\frac{y}{\varrho}\right)^{1/n}$$

i.e. $$\sigma = C y^{0.111}$$

where C is a constant depending on the curvature and is given by :—

$$C = \frac{\sigma_0}{\varrho^{0.111}}$$

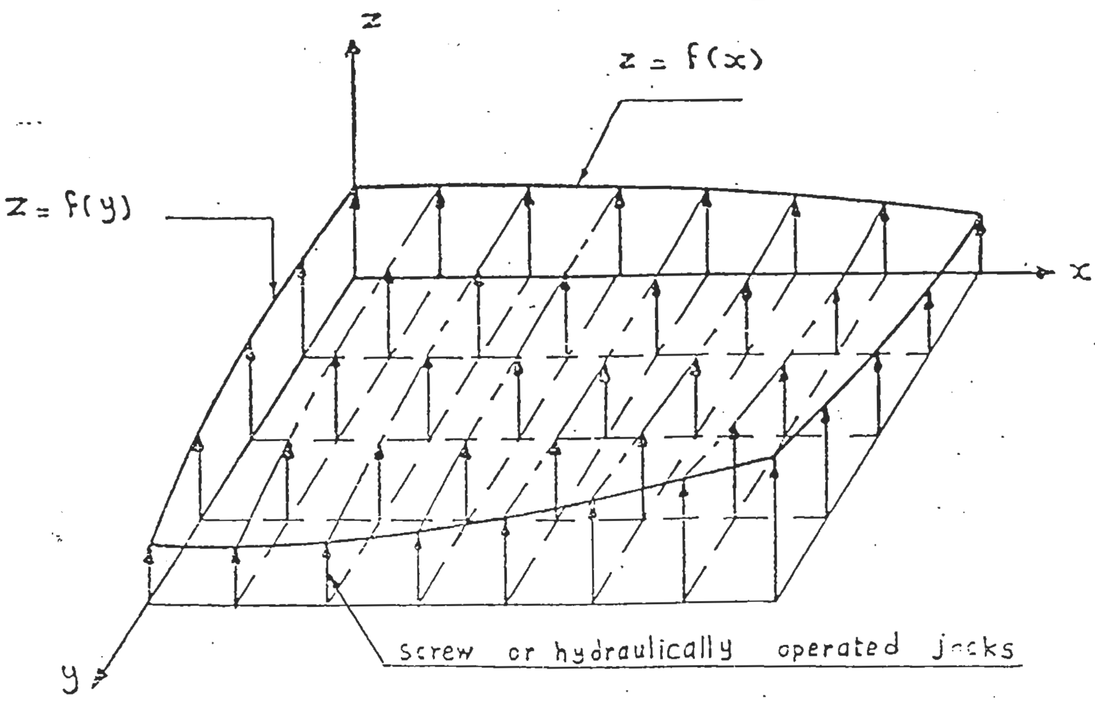

Fig. (1). A Telescopic Rig.

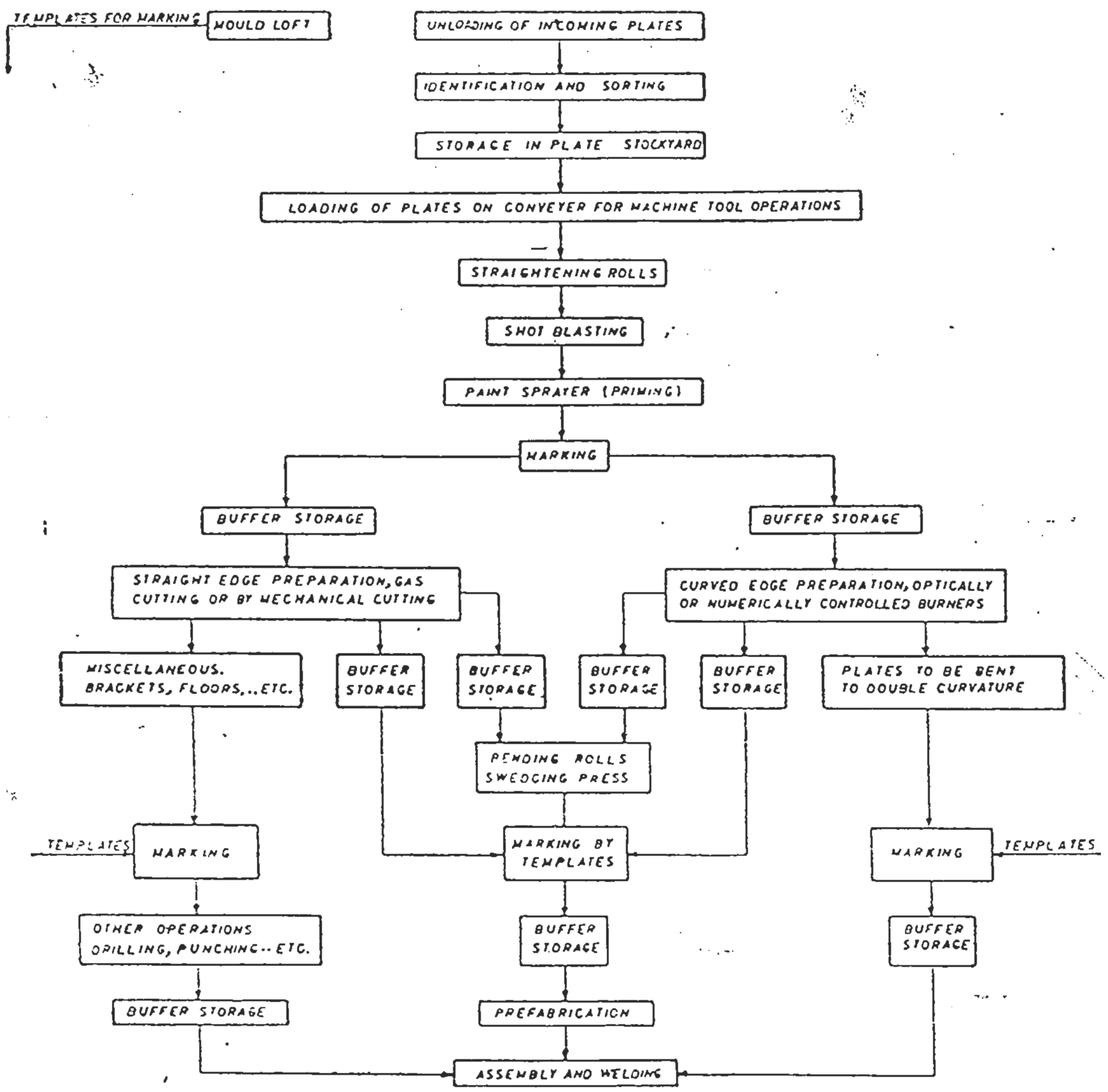

Fig. (2). Flow Diagram Of The Different Plate Operations.

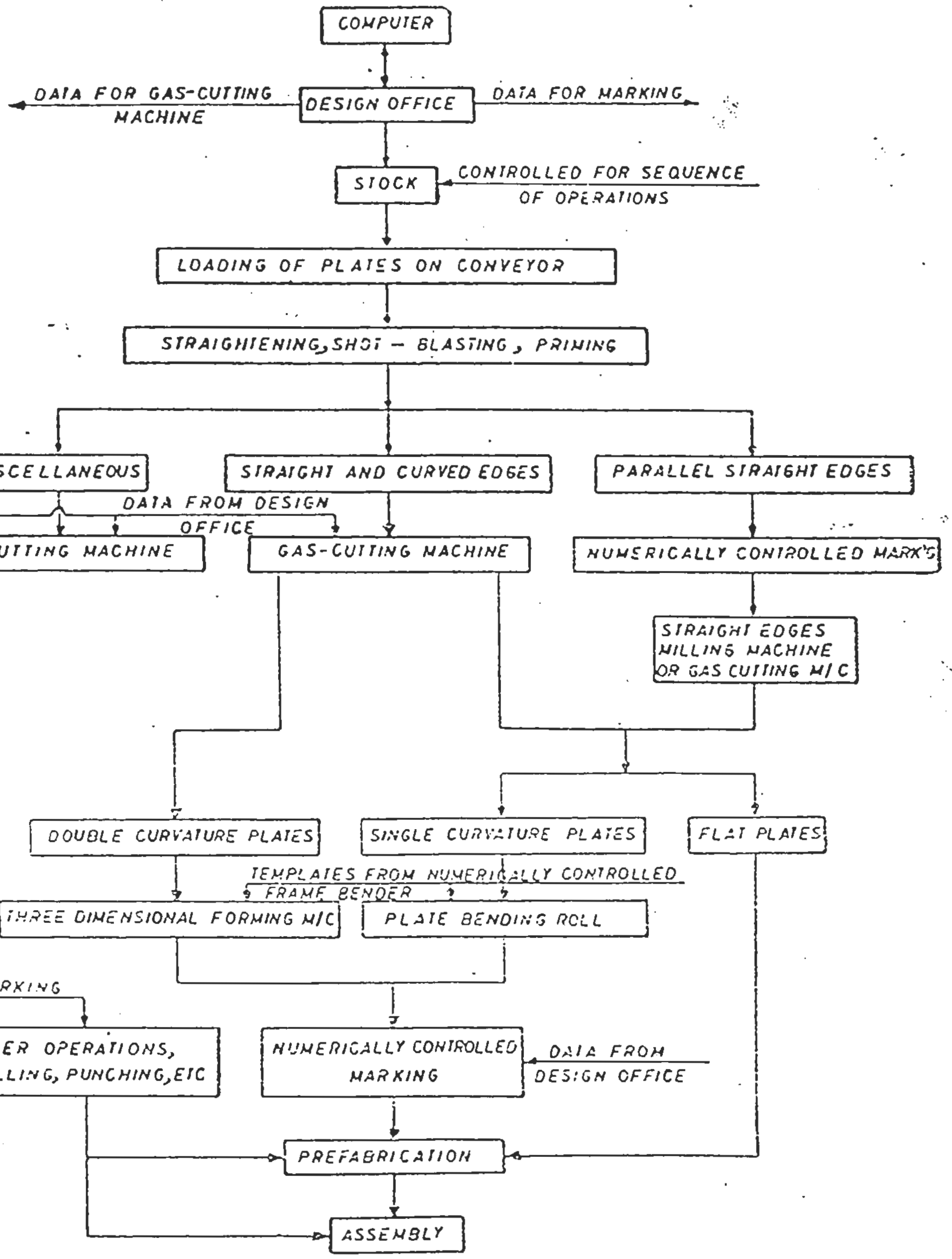

Fig. (3). Proposed Flow Diagram For Ship Plates Using Templates For Checking.

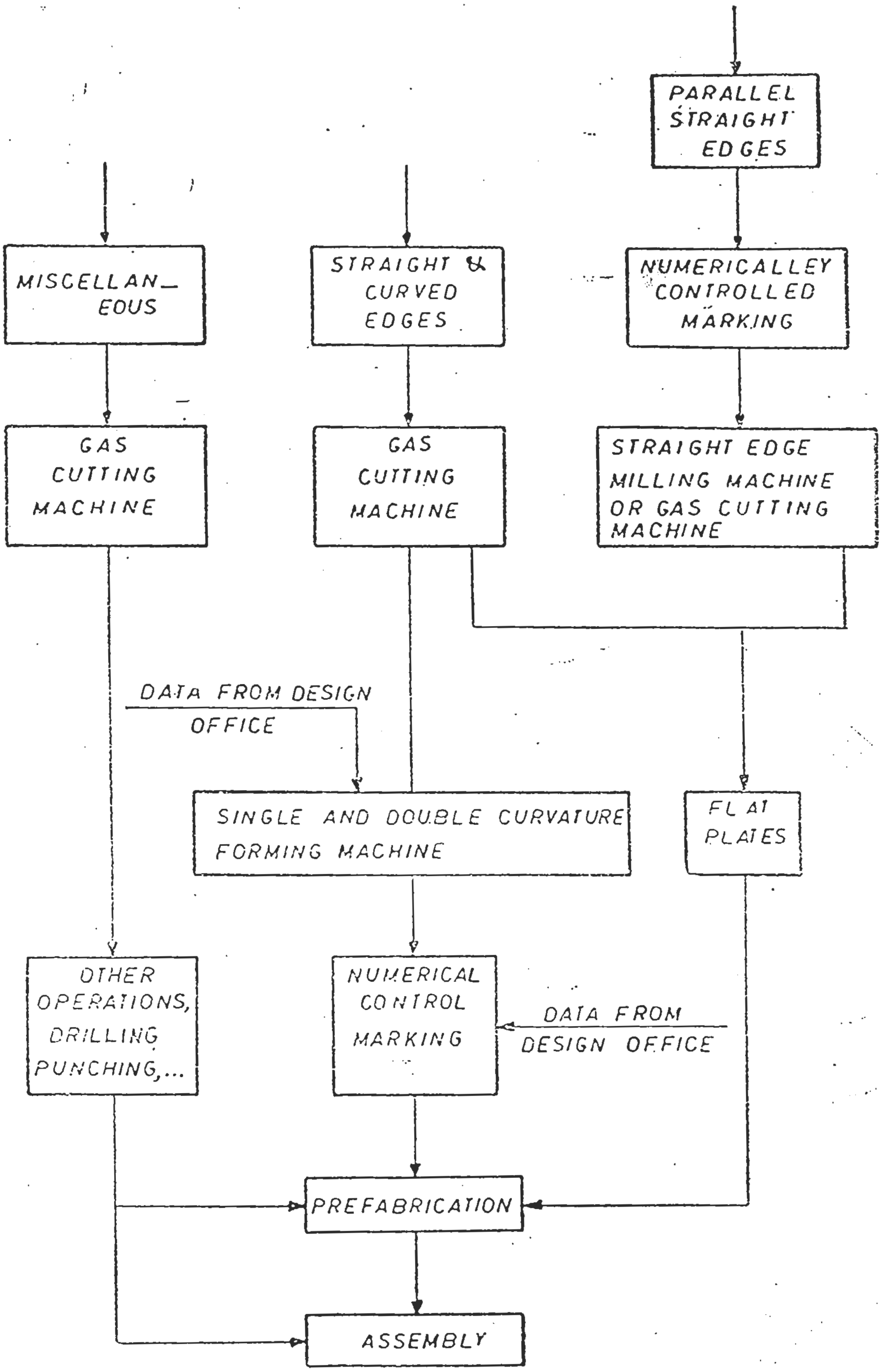

Fig. (4). Proposed Flow Diagram For Ship Plates Using A Numerically Controlled Plate Forming Machine.

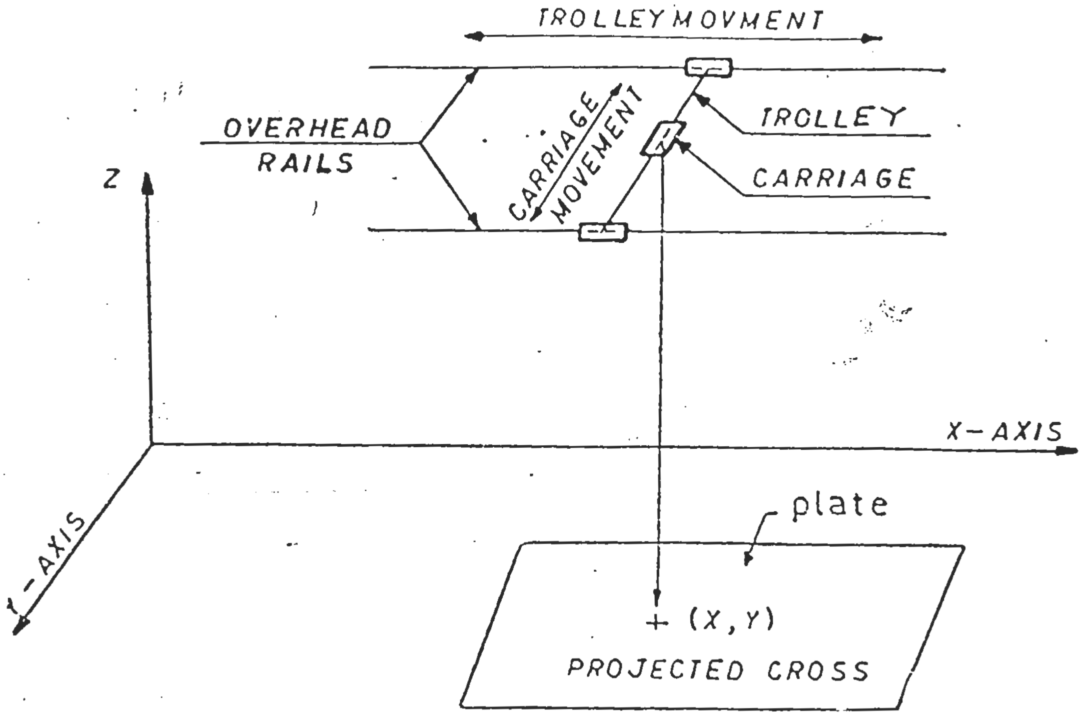

Fig. (5). Numerically Controlled Plate Marking.

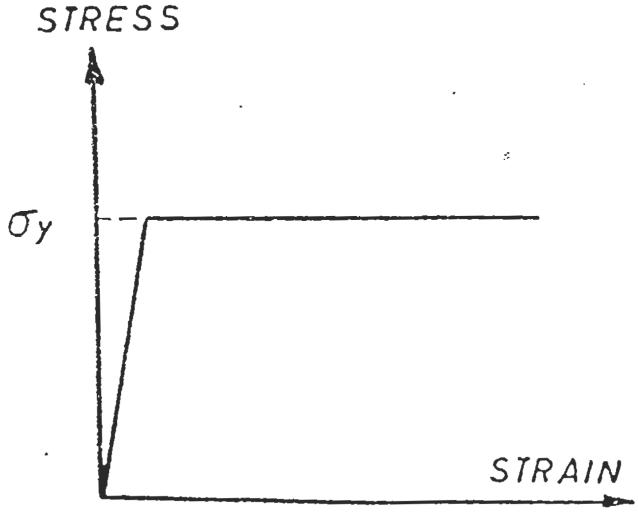

Fig. (6). Ideal Stress-Strain Diagram.

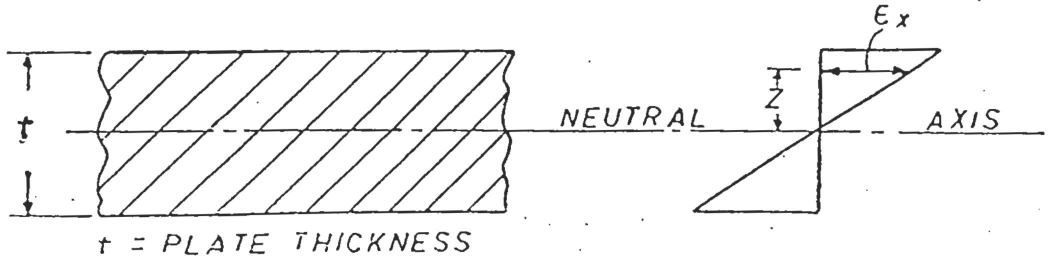

Fig. (7). Strain Distribution Across The Plate Thickness.

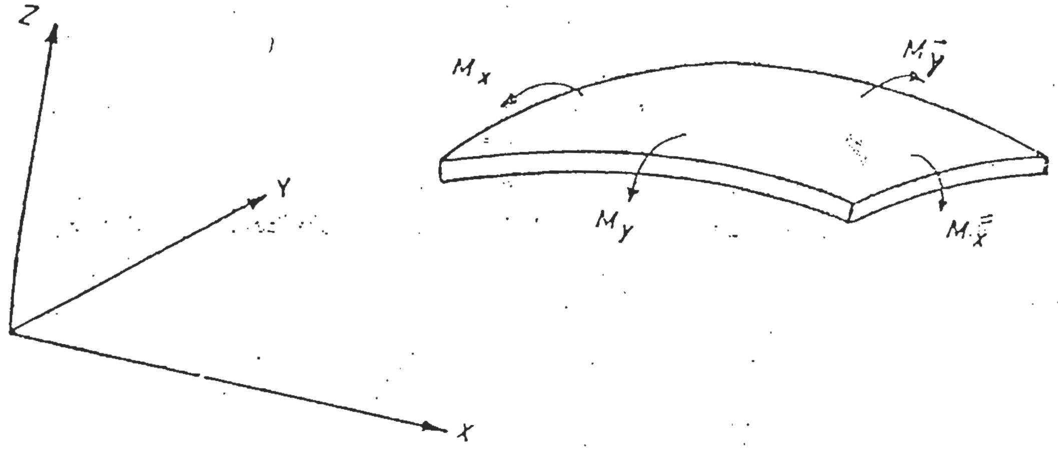

Fig. (8). A Plate Bent To Double Curvature.

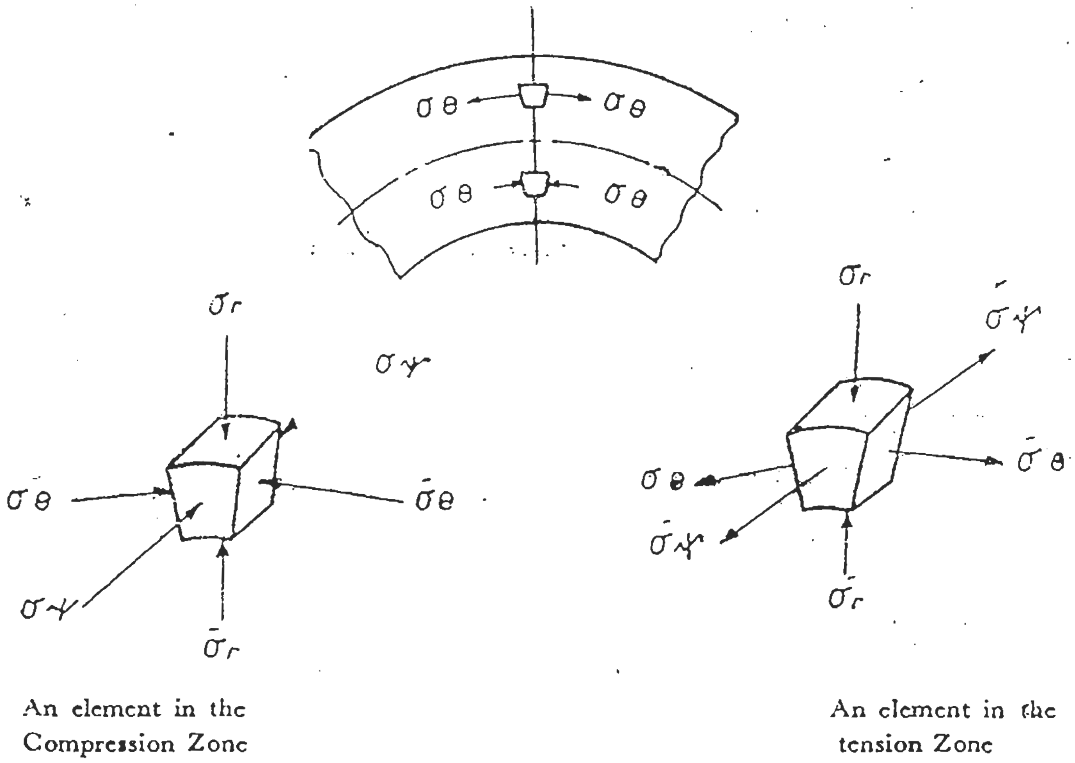

Fig. (9). Stresses On Two Different Elements Across The Plate Thickness.

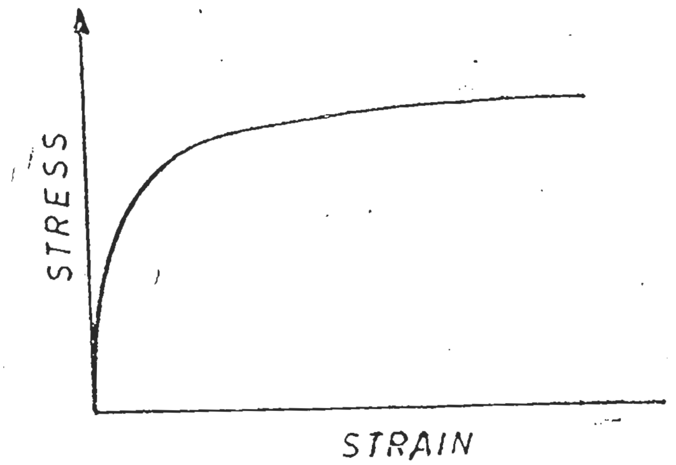

Fig. (10). Stress Strain Diagram With Non-Linear Strain Hardening Range

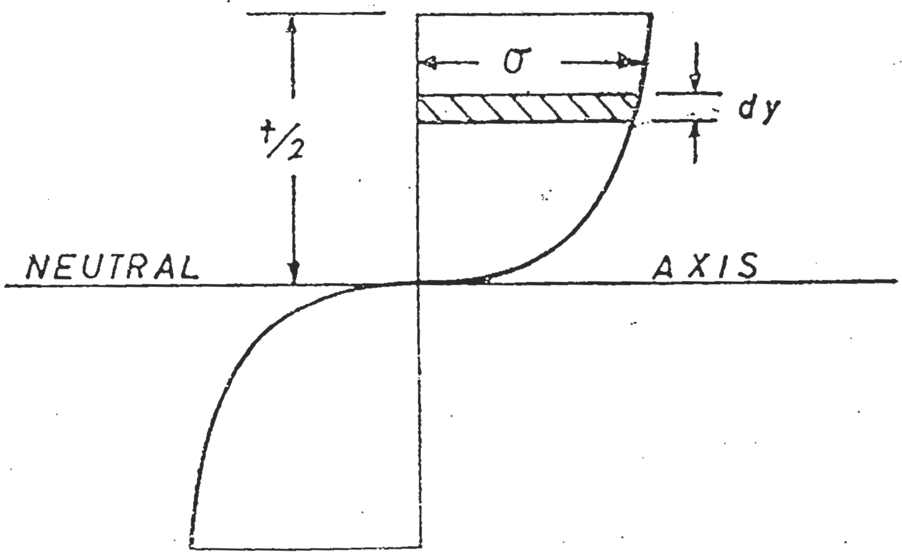

Fig. (11). Stress Distribution Across The Plate Thickness.

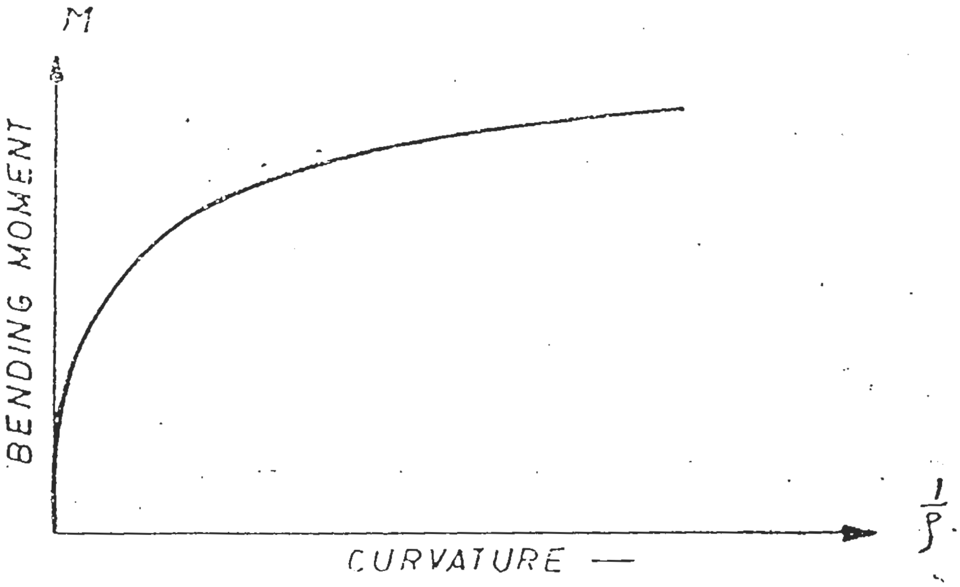

Fig. (12). Bending Moment-Curvature Relationship.

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