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Autor: McNeice, Gregory Malcolm

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Free form dam design - An art with scientific control

Desing de barrage, à géométrie variable.
Un art avec des contrôles scientifiques

Entwurf von Daemmen mit beliebiger Form.
Eine wissenschaftlich gelenkte Kunst

GREGORY MALCOLM McNEICE
Associate Professor Solid Mechanics Division University of Waterloo
Waterloo, Ontario - Canada

1.0 INTRODUCTION

In this world of automation,
mass production and renovation,
the engineer has little time
to test, retest and redesign.
Indeed, he needs computer assistance
to shape, to view and check resistance.
It is with assistance of this kind
the engineer turns artist with a scientific mind.

These few words summarize both the purpose and the product of the research outlined herein. The purpose was to develop a comprehensive design system which would allow a rapid preliminary design of an arch or arched gravity dam. That is, within a work week the designer should be able to complete the design cycle a sufficient number of times to produce his preliminary structure. In order to do so the system must be easy to use in the sense of preparing input data. It must perform a thorough stress analysis and provide visual output for rapid evaluation. Such a system has been the subject of a co-operative research effort between a Canadian company and University of Waterloo personnel. Although the final product is scheduled not to be finished before the fall of 1974, the major components are now operative and these will be described briefly in the following sections. Of particular interest is the three dimensional stress analysis portion of the system and the development of physical models for both architectural and test purposes.

2.0 THE FREE FORM CONCEPT

The arch dam is one of the few structures in civil engineering design that requires the master's hand in shaping it. The design is assessed through approximate stress analysis techniques and if not sufficient the shape is altered until the basic design criteria are satisfied. An experienced dam designer is, in the truest sense of the word, an artist. He sketches the arches on the site contour map in a manner that will provide both thickness and double curvature in proper proportions, resulting in as thin a structure as possible, but with a stress field that does not exceed the design limits. Obviously, even an expert designer cannot know absolutely if his particular shape is an optimum with respect to his criteria. Research has been directed toward the optimization problem [1]. However, this was a two dimensional structure only and it has never been shown categorically that such a model is accurate enough in the lower portions of arch dams. More important is the fact that most dam designers still prefer to shape the structure by hand. Consequently, he should be able to do this comfortably without being confined to specific geometry that may be dictated by the next design stage such as analysis. Because of the analysis methods such as simplified cylinder theories [2] or more advanced grillage techniques like trial load [3], the designer must use a conic section to describe a horizontal arch. Typical conics in use are circles, parabolae and ellipses. With computer assistance the processes have been expanded to multi-centered curves [4] in order to fit the shape to the valley more closely. The concept of free form shaping alleviates most of these difficulties and allows the designer to mould the dam more freely to the valley contour. One must remember, however, that construction practices and associated changes might also have to be adjusted if radical departure in shaping is allowed. Recently, a chief engineer of one Canadian firm who was the first to develop the free form concept [5] has provided constructional data for immediate use [6]. The approach Stensch used involved the use of elliptical segments that are overlapped such that at common free form points they have continuous slopes. Once a set of points is selected on each arch at the various elevations, elliptical segments are fitted both vertically and horizontally. The resulting grid of segments allows any point of a surface to be determined geometrically. The FAD system [6] has been used in providing designs for a number of dams recently [7]. A second free form approach has been developed at the University of Waterloo [8] in which parametric cubic splines are used to shape the dam. Figure 1 illustrates a set of typical free form points. The computer system called STRIDE (STRuctural Interactive DEsign) provides the designer with the capability of shaping his dam using only free form point input data. These points are chosen using the contour drawing prepared for the design. The point co-ordinates are obtained using an electronic digitizer table shown in Figure 2. The contours are also digitized and input to STRIDE. The system then fits the dam into the valley finding the intersection with the valley contours. At the designer's discretion STRIDE will provide computer plots of any number of horizontal and/or vertical sections such as illustrated in Figure 3. If a composite plot is desired, it can also be requested (see Figure 4). Reshaping can be done by simply moving one or more free form points and resubmitting the data. Once the shape has been decided upon, a peripheral outline of the upstream developed view is plotted. This plot is then used to begin the analysis phase. This is discussed in the next section.

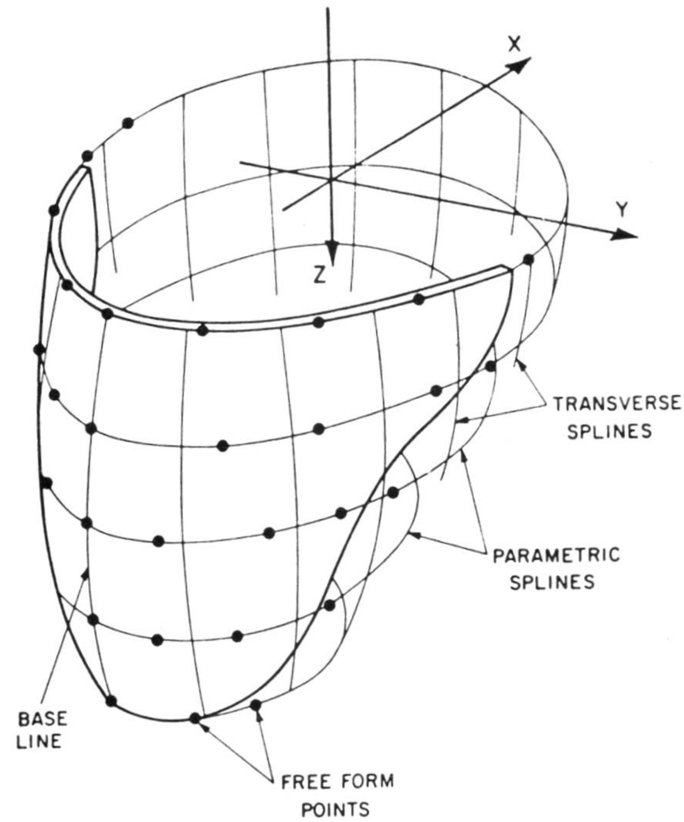

Figure 1 - Free Form Points for Spline Interpolation

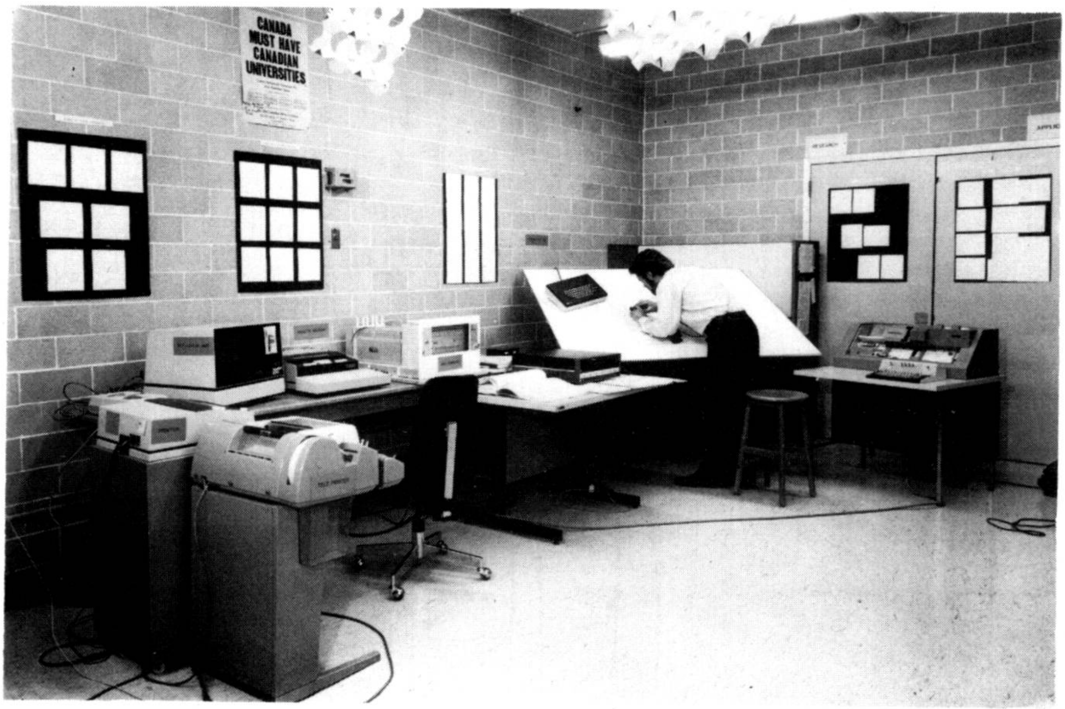

Figure 2 - Shaping Dam Using Digitizer Table

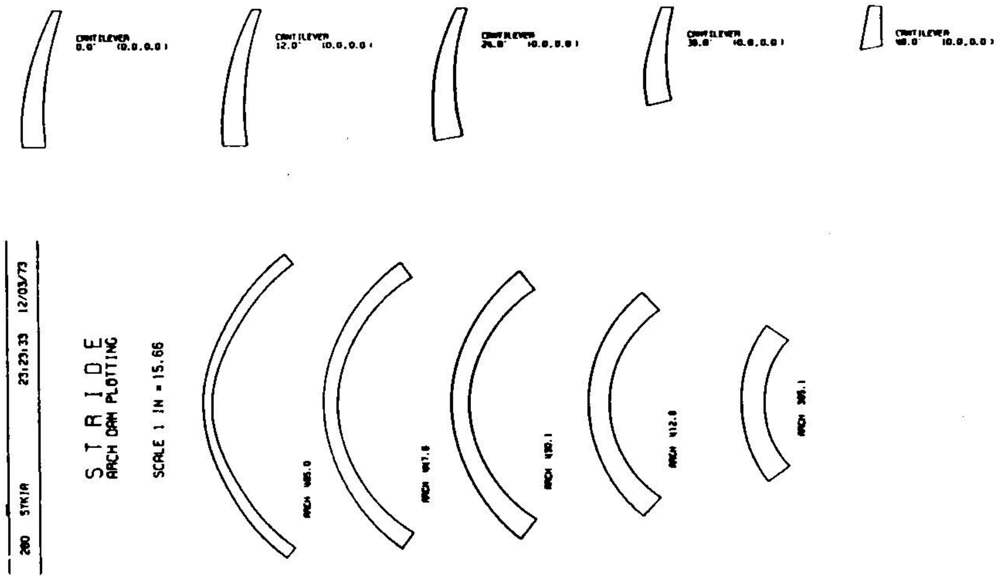

Figure 3 - Computer Plot of Horizontal and Vertical Sections

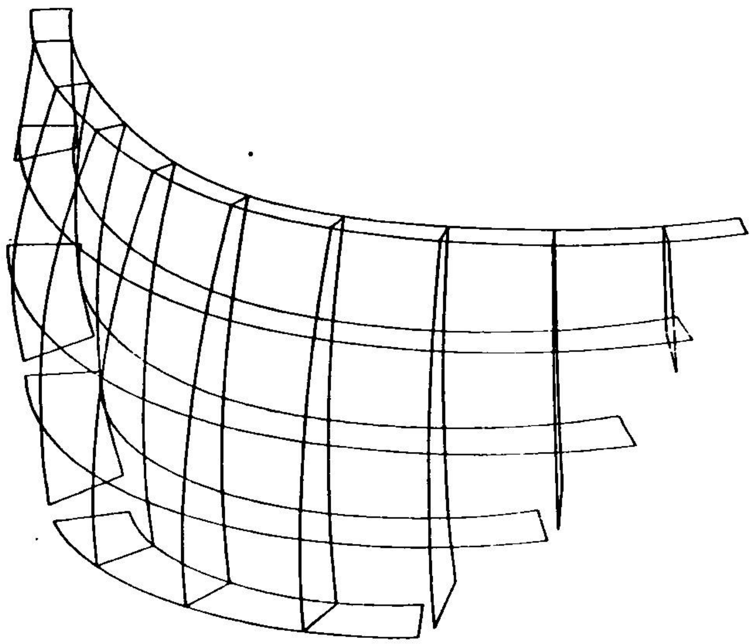

Figure 4 - Composite Plot of Sections

2.0 FINITE ELEMENT ANALYSIS

The finite element method is used in the analyses of the dams. A three dimensional model using curved boundary hexahedron elements is used since the lower one third of most arch dams are thick compared to the corresponding span length and three dimensional stress fields are usually present. The trial load method which is still used extensively is a two dimensional arch grillage method which fails to model stresses in the thicker regions of the structure. Also, for arched gravity dams, a three dimensional analysis is mandatory.

The amount of data required for a three dimensional finite element analysis is often large and should not be prepared manually. The data must contain element numbers, node co-ordinates and element incidences (20 for each element). The STRIDE system automatically produces this data. This is done following a selection of a mesh of elements by the designer. He uses the developed view outline as provided by STRIDE and sketches a two dimensional mesh of elements such as in Figure 5. With the mesh selected, the corner node co-ordinates are next digitized in a specific order. The data is input to STRIDE and the system creates the corresponding three dimensional mesh seen in Figure 6. All the necessary data required from this mesh for the analysis is produced by STRIDE and is given as input into the finite element analysis system. This system automatically calculates and applies surface, body and temperature loads, once the reservoir level along with the water and air temperatures are given.

For boundary support a finite element Vogt boundary model [9] is employed. This response is based on the same model used in trial load analysis [3] along with necessary corrections [10]. The Vogt model provides stiffness coefficients which simply add into the finite element structural stiffness matrix.

Once the stress analysis is complete the analysis system will plot various output in accordance with the selection made by the designer. Geometry plots can include single elements, groups of elements or the entire structure. Viewing angles relative to all three cartesian axis can be specified freely. Figure 7 illustrates one such plot. The same structure viewed from a different angle is seen in Figure 8. Here, a deformation plot is presented showing the original and the deformed shapes.

The most important output plots are those containing stresses. Although sectional stress plots are available, the most common type is the principal stresses on developed views of upstream and downstream surfaces. Figures 9 and 10 illustrate two of the choices available. That is, stress arrows with or without the element mesh and with or without node numbers and stress values. With stress plots such as these, the designer can assess his design quite easily. Therefore, having these two computer systems, one for shaping and viewing and the other for analysis, the engineer can rapidly shape and assess his design without preparing manual data.

In addition to the numerical model, a physical model would provide a final realization and also allow physical testing if desired. A brief account of the techniques involved in producing such a model is contained in the next section.

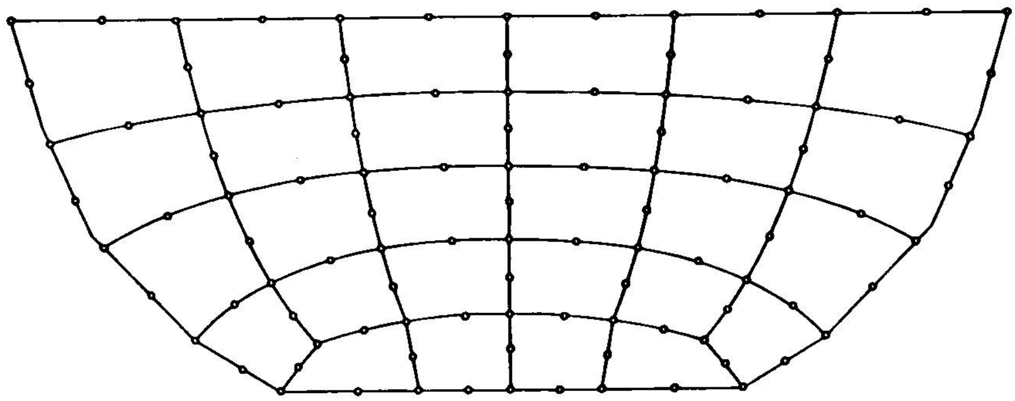

Figure 5 - 2-D Sketch of Element Mesh Made On Developed View of Upstream Face

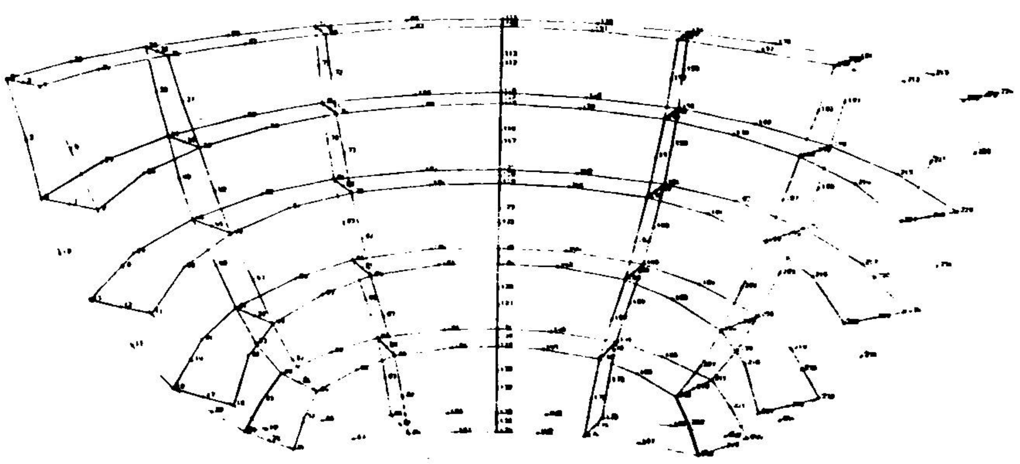

Figure 6 - Corresponding 3-D Element Mesh Produced by STRIDE

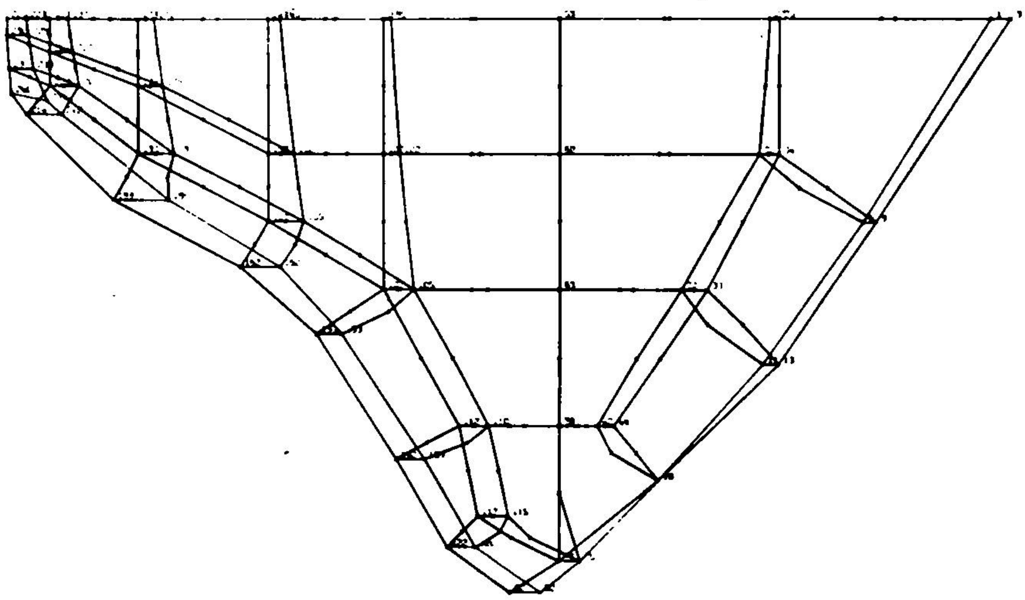

Figure 7 Computer Plot of Complete Dam Structure - Orientation is Optional

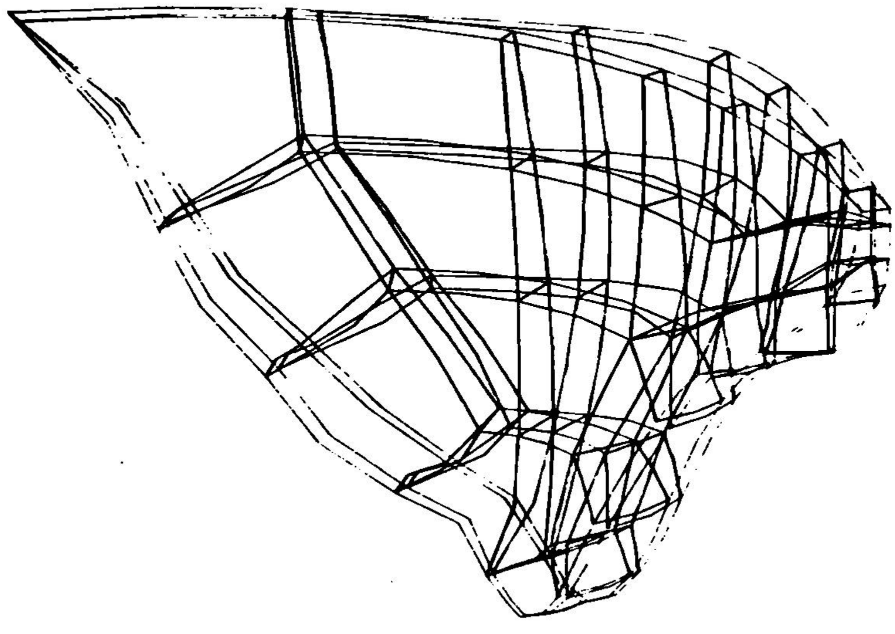

Figure 8 - Computer Plot of Structure Before and After Loading

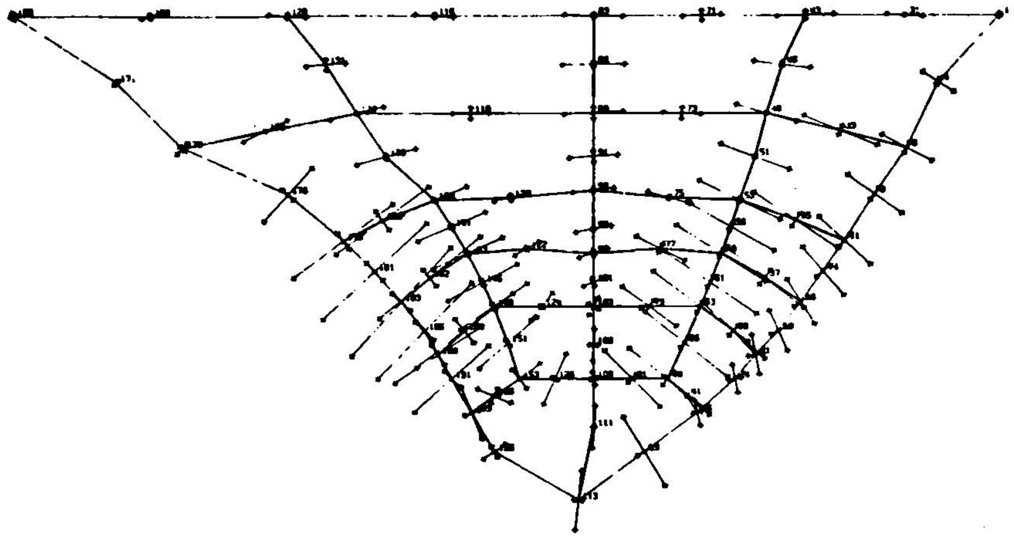

Figure 9 - Principal Stress Plot on Developed View of Downstream Face with Node Numbers and Mesh

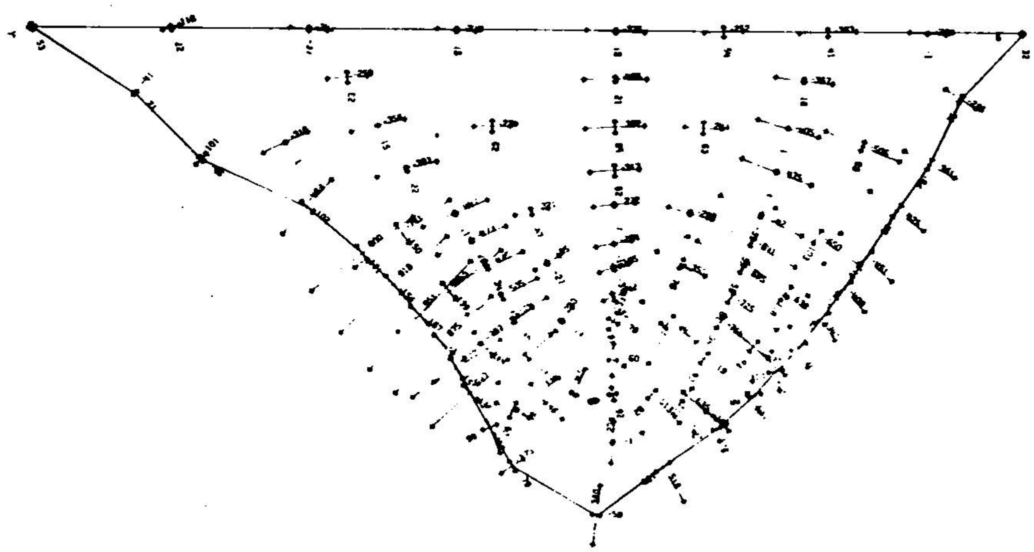

Figure 10 - Principal Stress Plot on Developed View of Downstream Face with Stress Values and Without Mesh

3.0 PHYSICAL MODEL PRODUCTION AND TESTING

A physical model of the dam serves two purposes. Firstly, in a preliminary design it can be used for architectural purposes. For a final design, a larger scale model can be tested in order to check numerical results provided by the analysis system.

At Waterloo the models are produced using the numerical control (N/C) machine in Figure 11. The spline description provided by STRIDE is used on the N/C machine to produce a negative mold as seen in Figure 12. Both contour and dam geometry are used. This mold is then used to produce the positive model as illustrated in Figure 13. For architectural purposes either plaster of Paris or any other appropriate material can be used. For physical testing, a larger scale model is produced. A photoelastic material is then used. Using a stress freezing technique, slices of the structure such as seen in Figure 14 can be used to determine stresses using photoelasticity. The finite element analysis provides an indication of what slices should be made. These can be tested and compared with numerical results. Although, preliminary efforts at producing models and stress freezing have been very successful, insufficient analyses have been done to date to warrant additional comment herein. The models do, however, add a new dimension to the concept of computer-aided design systems.

4.0 ADDITIONAL APPLICATIONS OF THE COMPUTER SYSTEMS

As an example of the versatility of the system, analysis of an arch similar to the central arch of the Manic 5 dam in Figure 15 was carried out by finite elements. The automated boundary and load parameters were calculated by the system without difficulty. A geometry plot is presented in Figure 16.

A second example that illustrates the potential use of the system for research studies is the investigation of construction stresses and simulation of construction stages. Figures 17 through 20 show four of seventeen different construction stages that were analyzed for a symmetrical dam. The object of this research is to compare the incremental construction stress results with those assumed to exist in the "as built" condition. Both vertical block and horizontal layered construction are being investigated.

A final example showing direct application to arched gravity dams is seen in the computer plot of the Hoover dam [11] in Figure 21. At the time of writing, efforts were being directed toward this type of structure. The same basic system can be used again.

Figure 11 - Numerical Control Machine Used to Produce Arch Dam Models

Figure 12 - Negative Mold of Arch Dam and Valley

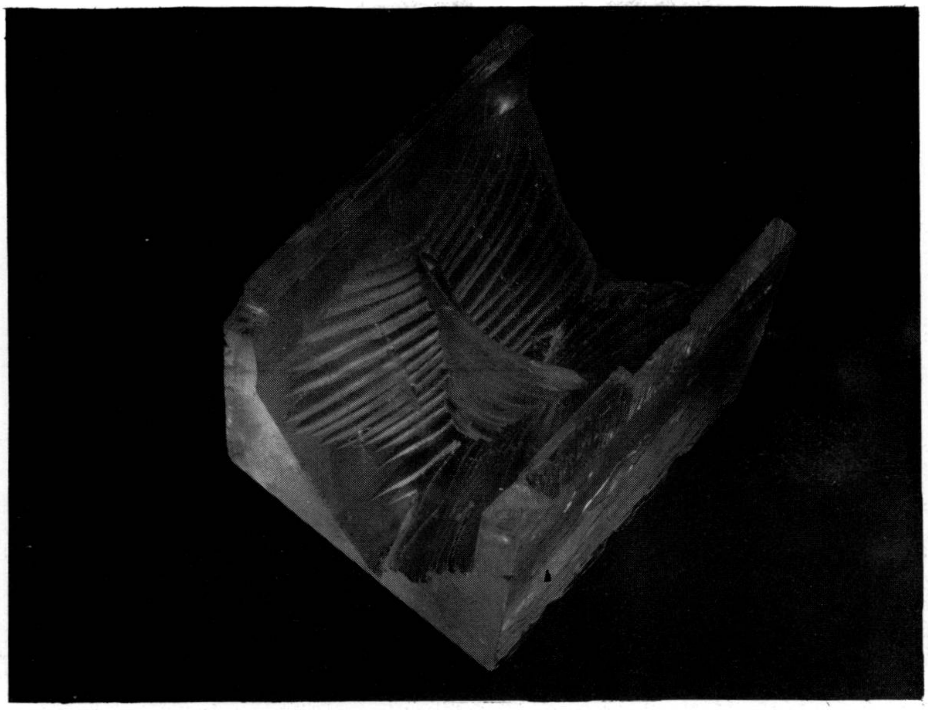

Figure 13 - Model of Arch Dam and Valley Produced From Negative Mold

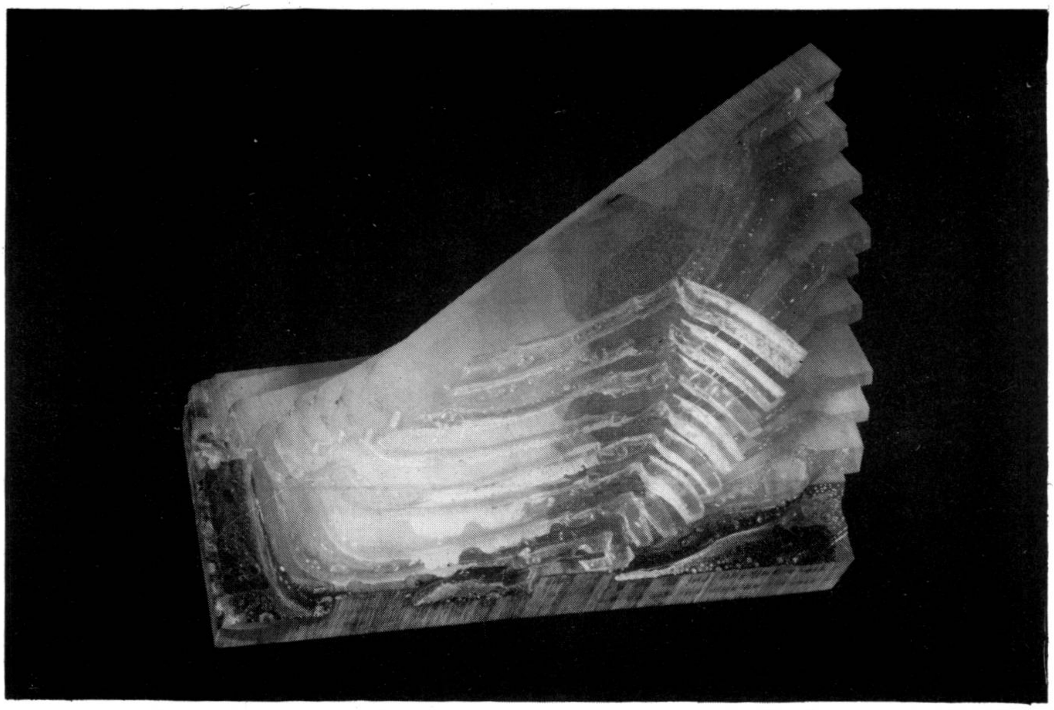

Figure 14 - Slices of Model Containing Frozen Stresses
to be Studied Photoelastically

Figure 15 - The Daniel Johnson Dam (Manic 5)

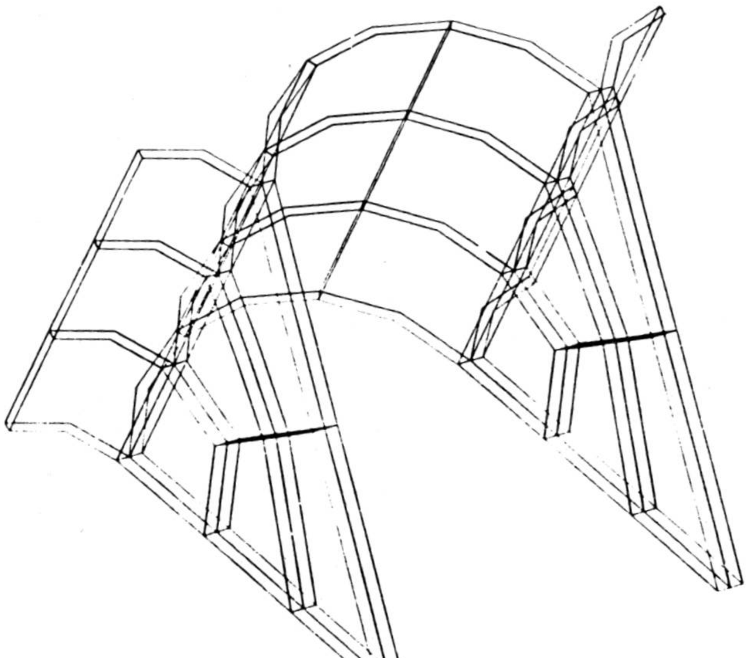

Figure 16 - Computer Plot of An Arched Structure with Buttresses

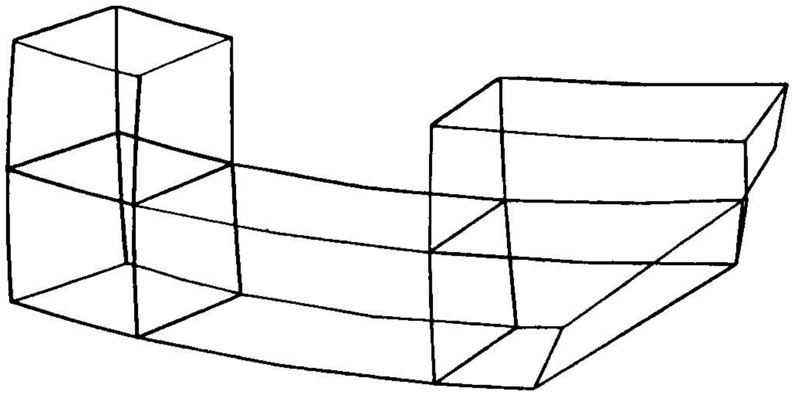

Figure 17 - Construction Stage 2 - 5 Elements

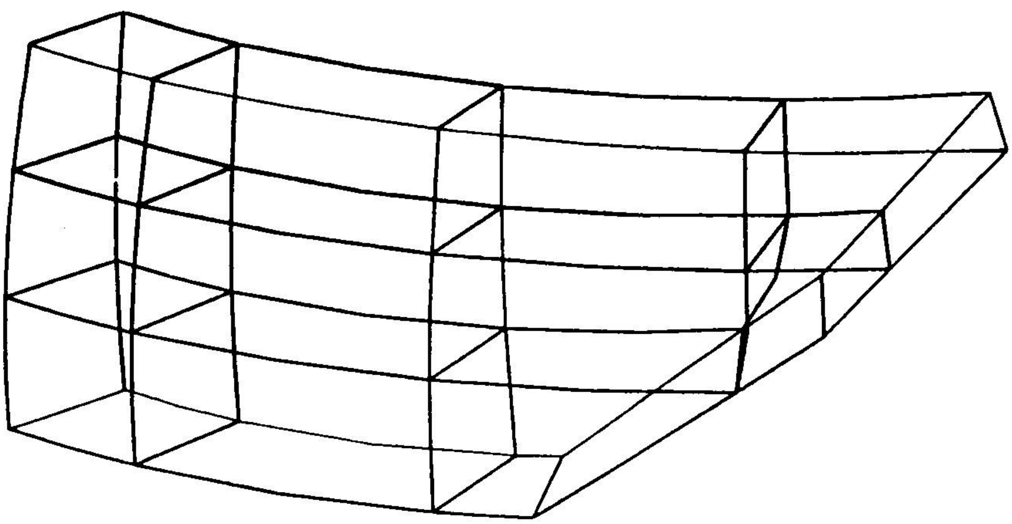

Figure 18 - Construction Stage 5 - 11 Elements

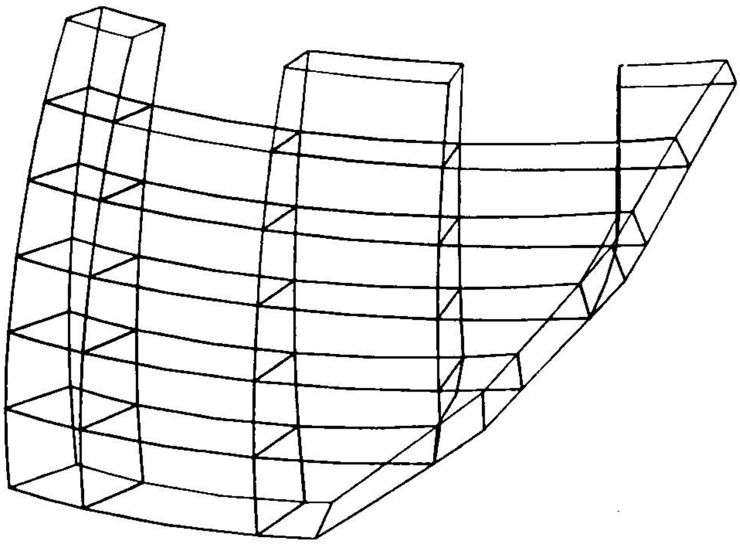

Figure 19 - Construction Stage 10 - 24 Elements

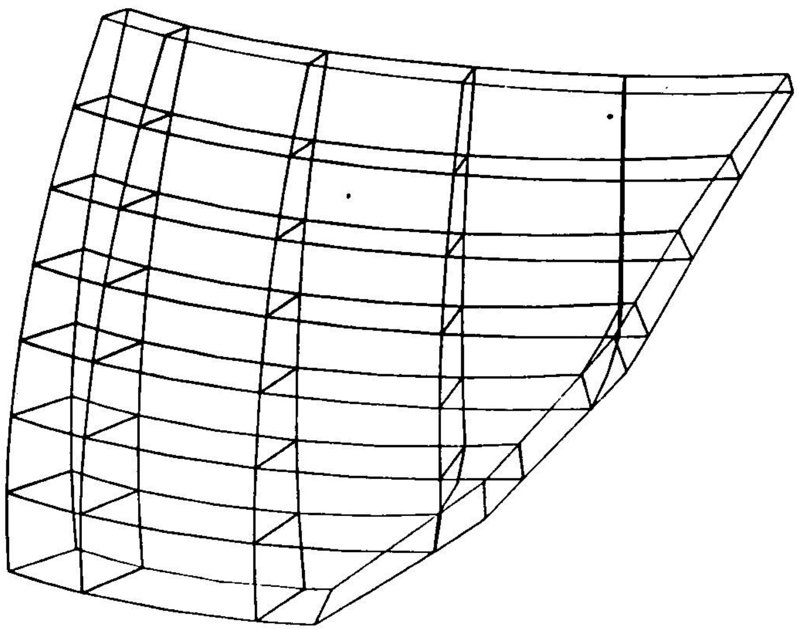

Figure 20 - Construction Stage 13 - 31 Elements

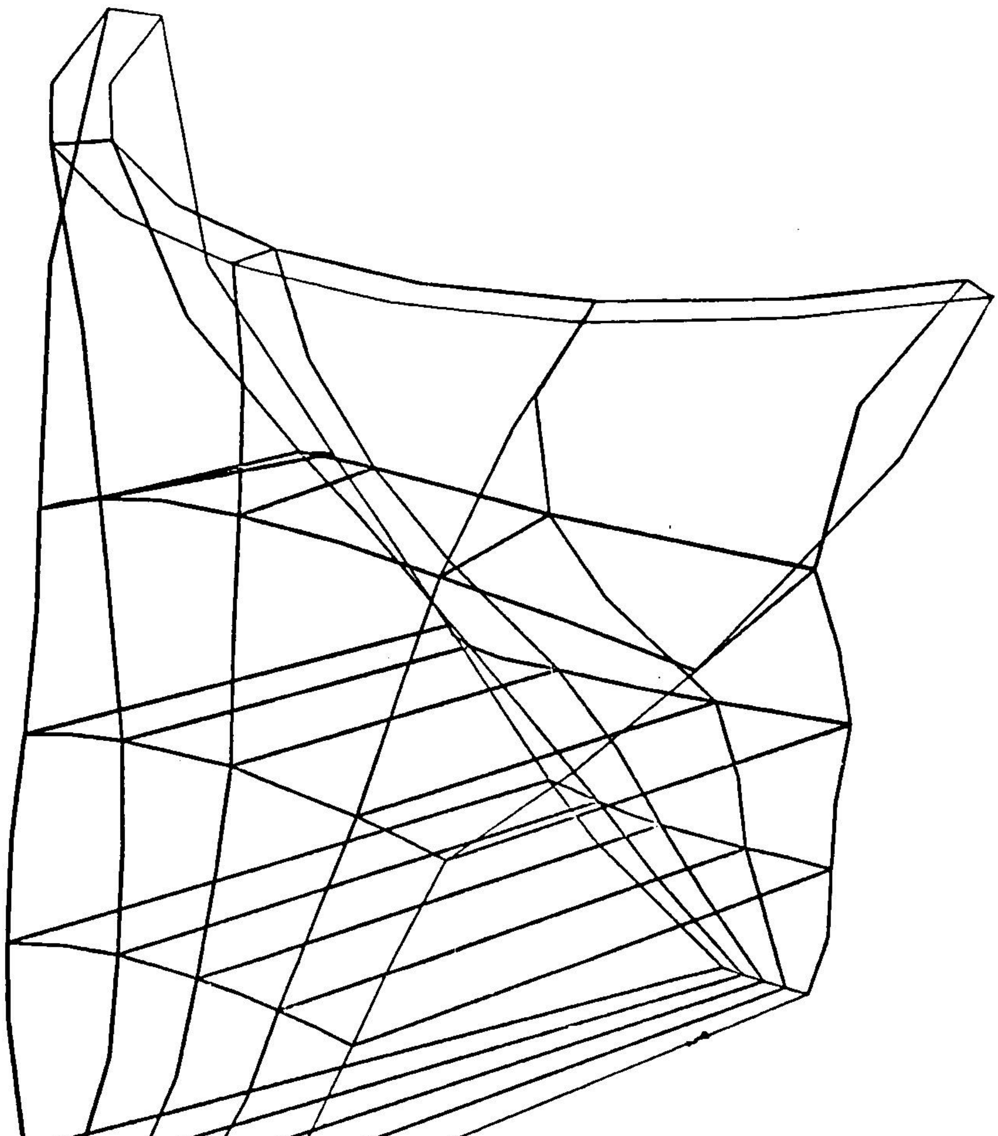

Figure 21 - Computer Plot of Hoover Dam

5.0 CONCLUDING REMARKS

The research reported herein clearly illustrates the power of computer systems in dealing with engineering designs such as arch and arched gravity dams. The introduction of free form shaping opens new avenues of providing custom built dams which fit the valley and satisfy the design criteria more readily. Graphical presentation of data from three dimensional stress analyses allows a rapid assessment of the design as well as provides finished drawings which can be entered directly into design and construction reports.

Physical models can be produced quickly and easily using an N/C machine. These serve as both architectural and test models. In short, the designer has at his fingertips a set of tools that allow him to be as creative as he wishes without spending many unproductive hours preparing manual data, sketches and drawings. For the researcher, these systems provide a great opportunity to study various aspects of structural behaviour which hitherto would have been untenable. However, verification of test results and numerical calculations of stresses can only be made in accordance with prototype response. Efforts are currently underway to provide this data on the Idikki Dam in Kerala State, India [12] [13] [14]. The system reported herein has been used extensively for research on that dam. Some results have been reported in reference [15].

Research into construction stage stresses in arched gravity dams as well as the stress analysis around openings such as galleries has begun using the system reported herein.

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Summary

The paper describes computer systems which allow the dam designer to shape arch and arched gravity dams rapidly and freely. Spline functions are used to describe curved surfaces established using points in space. Finite element, three dimensional stress analysis is automatically performed by a second system that is supplied input from the Free Form system. Computer plots of stresses and geometry are illustrated. Applications of the systems to research investigations are also presented. Physical models of the dams are produced using a numerical control machine along with the data from the previous systems. Photoelastic stress freezing test techniques are indicated.

Résumé

L'article décrit des systèmes basés sur l'ordinateur qui permettent à un technicien d'effectuer rapidement et sans contraintes le design de barrage-voûte ou de barrage-poids en arc. Des fonctions spline sont utilisées pour décrire des surfaces courbes à partir de points dans l'espace. Le systeme de design à géométrie variable envoie des données à un deuxième système qui effectue automatiquement l'analyse par éléments finis, des contraintes tridimensionnelles. Des graphiques de la géométrie et de la distribution des contraintes sont produits par l'ordinateur. Divers cas d'application a la recherche sont présentés. Des modèles physiques de barrages sont produit à partir d'une machine à contrôle numérique et des données des systèmes précédents. On présente enfin des techniques d'évaluation des contraintes avec des matériaux photoélastique à froid.

Zusammenfassung

Die Arbeit beschreibt Computer-Systeme, die es dem Entwerfer erlauben, Bogen und Schwerkraftdaemme schnell und unbeschraenkt zu gestalten. Um an vorgegebene Raumpaukte gebundene, gekruemmte Flaechen zu beschreiben, werden Spline-Funktionen benutzt. Durch ein zweites System, das seine Eingaben von dem ersten, die freie Form des Dammes bestimmenden System erhaelt, wird automatisch eine drei-dimensionale Spannungsuntersuchung mittels der Finite-Element-Methode durchgefuehrt. Computer-Diagramme von Spannungsverteilung und Geometrie werden vorgefuehrt. Ebenso werden Anwendungen der Systeme auf Forschungsaufgaben gebracht. Modelle des Dammes werden, unter Verwendung der durch die zuvor erwaehuten Systeme gelieferten Daten, mittels numerisch kontrollierter Maschinen hergestellt. Ferner wird gezeigt, wie ein Verfahren zur Pruetung der numerisch gewonneuen Resultate angewendet werden kanu, das auf dem photoelastischen Einfrierverfahren beruht.