

INTEGRATING ANALYSIS AND DESIGN IMPROVEMENT IN A REVERSE ENGINEERING FRAMEWORK

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Abstract *¾ The purpose of this research is firstly to develop an improved method for implementing reverse engineering by integrating engineering analysis within the reverse engineering framework. Secondly, the literature publication of this research will expose mechanical engineering students taking Mechanical Design Technology course to the larger perspective of reverse engineering.*

Instead of creating just the CAD model, a FEA model complete with nodes and meshes, loading and boundary conditions is generated allowing for critical part performance information to be predicted. Costly and time consuming destructive or non-destructive testing on the part is eliminated.

The results of this study will make the task of reverse engineering an existing part and producing an improved part greatly simplified and structured. A significant benefit that is provided by the new RES is the total cost savings due to more efficient manufacturing and prototype testing of the clone part, thus improving productivity.

Index Terms *¾ CAD/CAM: Computer-aided Design / Computer-aided Manufacturing, CMM: Coordinate Measuring Machine, RES: Reverse Engineering System, NRES: New Reverse Engineering System.*

INTRODUCTION

Reverse engineering is the process by which an existing part or a physical model is recreated or cloned. The reverse engineering system starts with either a contact or non-contact data acquisition technique, followed by CAD system for model regeneration. The model is subsequently integrated into a CAD/CAM system for tool-path generation and completed with automated manufacturing system. Unavailable or missing geometric data for existing parts can be acquired by contact or non-contact data acquisition techniques. Using this acquired geometric data, the CAD model of the part can be regenerated. Based on the CAD model, the part can be reproduced using a CAD/CAM system and a numerical control machine tool.

Mechanical Design Technology is a course offered for fourth year mechanical engineering students in Universiti Teknologi Petronas, Malaysia. The course cover topics from design to manufacture and reverse engineering being one topic.

Reverse engineering's applications are expanding rapidly from manufacturing to medicine. RES is also an effective tool for implementing concepts such as concurrent

or simultaneous engineering since it helps shorten design-to-manufacture lead time. In relation to this research, reverse engineering can be further defined as the process of building a CAD model from an existing part or prototype, allowing for engineering analysis and design improvement, before other manufacturing processes such as computer-aided manufacture and machining to obtain a cloned or modified part.

PROBLEM STATEMENTS

Two notable shortcoming in relations with reverse engineering currently: (1) the existing RES fails to provide critical performance information for the part being remanufactured, and (2) available literatures and publications on reverse engineering are not only very limited for engineering students but those available mainly focus on data acquisition rather than the overall perspective.

Current available reverse engineering systems lack the ability to analyze a part before its remanufactured. It could be a waste of effort to digitize a broken or worn part and later remanufacture the exact duplicate. For often times, breaks and excessive wear in parts are the results of poor design. Instead, it is feasible to analyze and redesign the part model, if necessary, eliminating inferior characteristics before remanufacture. This is extremely effective for identifying areas of concern such as safety and reliability before significant amounts of effort and money are spent on remanufacturing parts. Costly and time consuming destructive or non-destructive testing on the part are also eliminated. Such a situation would increase productivity and efficiency.

Research Significance

Integrating engineering analysis in the new reverse engineering system, NRES, provides data on the performance of the part before remanufacture, thus minimizing the possibility of remanufacturing parts with defects or deficiencies. Additionally, this effort will provide engineering students with a literature that encompass the larger perspective of reverse engineering. Students taking similar courses to Mechanical Design Technology which covers reverse engineering will be exposed from data acquisition, CAD model generation, engineering analysis, tool-path generation and manufacture.

Rules and procedures are formulated for conducting engineering design changes for design improvement. The task of reverse engineering an existing part and reproducing

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an improved part will be now be greatly simplified and structured.

Brief Procedure

The front-end of the reverse engineering process involves the reacquisition of CAD data from a part or prototype. Based on geometric data obtained by the contact method digitizing system from the Coordinate Measuring Machine, a wire-frame model is generated. The wire-frame model is divided into a mesh and node network. Load and boundary conditions are assigned to the model, transforming it into a finite element model. Engineering analysis is then conducted, and the performance results are analyzed. If necessary, modification for design improvement can be executed utilizing the procedure and rules developed in this research.

APPLICATION AREA

A large amount of research has been done in the area of reverse engineering. Although the approaches differ in many respects, none have integrated engineering analysis and procedures for design improvement. Here, some of the past and present research dealing with RES application areas, the framework of existing RES, and data acquisition techniques are reviewed.

Huang and Tai [2000] presents a method for pre-processing data points for curve fitting in their RES. Data points of an existing part is measured by a CMM and processed before fitting into a B-spline form. This method is implemented for a number of practical application.

Carbone et al. [2001] proposed a RES for complex, free form surfaces, based on the integration of the measurement information from a 3D vision sensor and a CMM. CAD model of complex geometry can be reconstruct with high accuracy and minimum human intervention.

Quality Machine of Loveland, Colorado developed and implemented a RES to remanufacture a thermoplastic elastomer handle. The handle attaches to a lever that controls a valve on a hydraulic machine. In their RES, Quality Machine utilized a non-contact data acquisition technique, a Digibot laser scanner, to digitize the handle. Based on the digitized geometric data, a 3-D CAD model of the handle is created. A CAD/CAM system, SurfCAM, in the RES is used to generate the NC codes required to machine the electrode to produce the mold. Before cutting expensive material, the tool paths were tested using NC proofing polyurethane foam. Their RES lacks critical performance information for the mold which could have been generated through engineering analysis by utilizing the same geometric data.

Most other research in RES focuses mainly on data acquisition while making a passing statement on the CAD/CAM component of their RES; none took the extra step of further utilizing the CAD model generated from the digitizing system to perform engineering analysis. Thus, this research attempts to contribute in the reverse engineering

framework by developing a procedure for integrating engineering analysis such that the NRES can provide additional information by predicting the performance of the part to be reverse engineered. Additionally, a methodology is developed to assist in conducting design changes for product performance and reliability improvement by providing rules and procedures for engineering design changes.

RESEARCH PROCEDURE

The framework developed for generating performance information through engineering analysis from the new reverse engineering system (NRES) is described and the structure is shown in Figure 1.

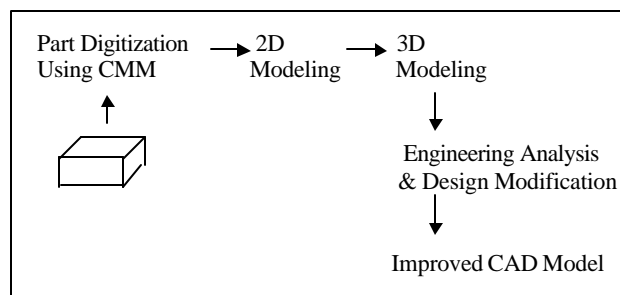


FIGURE 1
STRUCTURE FOR INTEGRATING ENGINEERING ANALYSIS
AND DESIGN MODIFICATION.

The geometric data of an existing part is acquired by a contact data acquisition method using a CMM. A wire-frame model of the digitized part is constructed based on the geometric data acquired. The critical performance information of the part to be remanufactured can be generated by performing engineering analysis. Instead of producing a prototype and testing it with either a destructive or non-destructive method, in this research, a finite element method is utilized as a tool. A procedure is developed to transform the wire-frame model into a format suitable for conducting finite element analysis. The part model is represented as a finite element model by breaking-up the wire-frame model into a finite number of smaller elements. Each element is in the shape of a hexahedral brick with eight nodes. Actual loading and boundary conditions are assigned to the model. Critical performance information regarding the linear stress and deflection data is collected. This data is compared to the known yield stress value of the intended material of the part. The yield stress value acts as the threshold for the linear stress value obtained from conducting the performance analysis. Any value exceeding the yield stress is an indication that the part has yielded under that particular loading condition. Considering safety factors, any stress value less than the yield stress but exceeding the safety margin is deemed as unsuitable.

Engineering changes are required to overcome deficiencies by making design modifications or selecting a superior material. A set of rules is developed in this research providing guidelines for making design modifications in the

NRES. Once design modification is completed, engineering analysis is again conducted to analyze the performance of the modified design. The iteration between design modification and engineering analysis is executed until a suitable design is accomplished.

Data Acquisition of the Sample Part

The isometric view of the sample part is shown in Figure 2. For this part the line/line intersection alignment is used since the part is of a prismatic shape with planar surfaces.

The digital measurement capabilities of a CMM allows the extraction or acquisition of engineering design data such as Cartesian coordinates, surfaces, and orthographic drawings from the existing part. The geometric data acquisition for the test part is implemented using a Brown & Sharpe MicroVal PFX coordinate measuring machine. Micromasure IV software is used for writing the data acquisition program. The complete digitizing program written for the geometric data acquisition generated for the test part is written for each elevation.

The mappings of all the views are used to generate the CAD model of the sample part, as shown in Figure 3, using the modeling module in the Algor system.

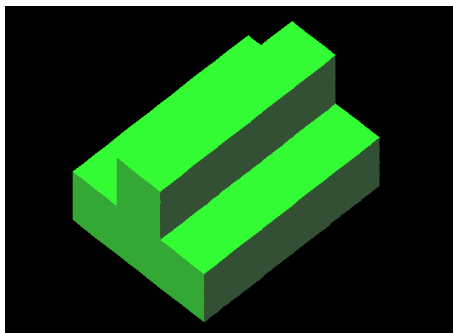


FIGURE 2
ISOMETRIC VIEW OF SAMPLE PART.

Procedure for Integrating Engineering Analysis and Design Improvement

The most crucial step in integrating engineering analysis, in reverse engineering, is transforming the wire-frame model into a proper finite element model. In this research, a procedure is developed for transforming the CAD model into a FEA model. The aim is to develop the most suitable mesh and nodal pattern that provides enough elements to obtain accurate results without wasting data interpretation and processing time.

With a 3D model, the choice of finite element is limited to volume elements such as tetrahedron, pentahedron, hexahedron, and solid or brick elements (Refer Figure 4). Three-dimensional analysis is preferred over two-dimensional analysis to analyze the result through-out the entire model rather than just a cross-section of the part. The brick element is selected over the other element types.

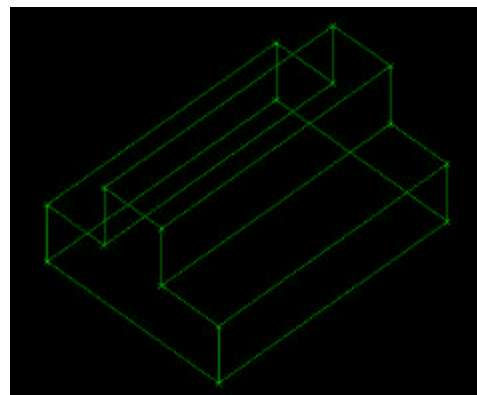


FIGURE 3
WIRE-FRAME MODEL OF THE DIGITIZED
SAMPLE PART.

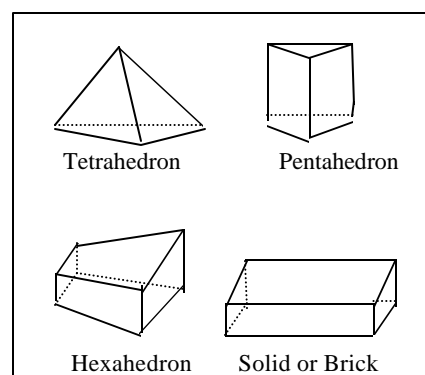


FIGURE 4
VOLUME ELEMENTS.

It was chosen based on its suitability and ease in dividing the prismatic part into finite elements. Tetrahedral, pentahedral, or hexahedral are usually necessary to accommodate irregularities in geometry.

Although finite element meshes should be uniform through-out the model, mesh refinement is performed at regions of rapid change in geometry [Champion; 1992]. Mesh refinement is required to obtain more accurate results especially of stresses rather than deflections. The reason being that stresses are calculated using derivatives of the displacements. Stresses calculated at adjacent elements may differ substantially if the finite element mesh is not adequately refined. A factor to be considered when conducting mesh refinement is the element aspect ratio. This is defined as the ratio between the element's longest and shortest dimension. Regions with small variation of stresses could have a 40 to 1 aspect ratio and still yield good results. As a general rule, an aspect ratio of about or under 10 and 3 for deflection and stress analysis, respectively, should be followed [Spyrakos; 1994].

In the part model being analyzed, the stress output at critical locations is where there is an abrupt change in the geometry. Corner nodes are difficult locations to compute

stresses. Unfortunately, in many cases peak stress occurs at corners, and their magnitudes may govern the design. Engineering design changes need to be executed to overcome concentrated stresses that may result in local plastic deformation. On the other hand, even with ductile materials, areas of stress concentration are possible sites for fatigue if the design part is cyclically loaded. Fillet radius may be introduced to reduce the stress concentration well below the material yield point with consideration to the safety factor.

In making design changes by introducing a fillet (Refer Figure 5 and 6), it is necessary to start with sharp fillet, gradually increasing to full or even blunt fillet if necessary [Avallone et. al; 1986]. These steps are necessary in order to achieve significant reduction in stress concentration. In application areas sensitive even to minimal deflection of the part, buttresses can be introduced to provide support against deflection.

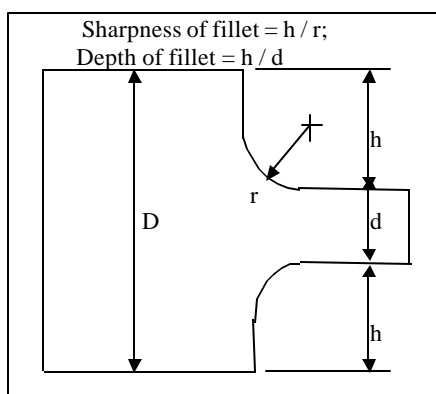


FIGURE 5
SHARPNESS AND DEPTH OF FILLET.

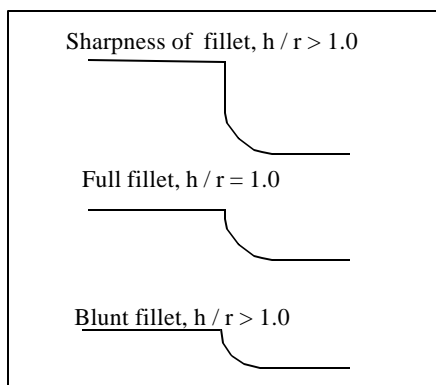


FIGURE 6
VARIOUS SHARPNESS OF FILLET

Engineering Analysis Procedure

The idea of implementing the procedure to integrate engineering analysis in the new reverse engineering system, NRES, is demonstrated using the sample part shown earlier

in Figure 2. The terms sample part and test part are used interchangeably in this research referring that part.

The aim of this procedure is to develop the most suitable mesh and nodal pattern that provides enough elements to obtain accurate results without wasting data interpretation and processing time. Considering that the sample part is prismatic in shape with planar surfaces, brick elements are selected, uniformly dividing the wire-frame model into a finite element model as shown in Figure 7. The nodes are all defined at load and support points.

Observing that the model as shown in Figure 7 consist of corners with rapid change in geometry between two coplanar surfaces, mesh refinement needs to be conducted (Refer Figure 8). To ensure that the analysis yield good results, element aspect ratio is kept under 3 for stress analysis [Spyrakos; 1994].

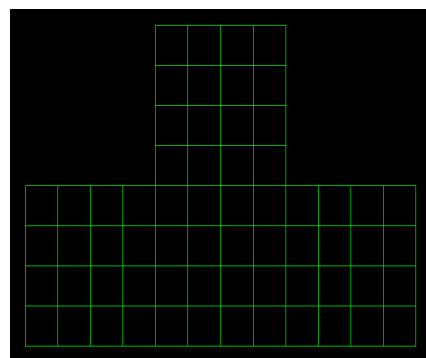


FIGURE 7
SIDE ELEVATION OF MODEL WITH UNIFORM BRICK ELEMENTS.

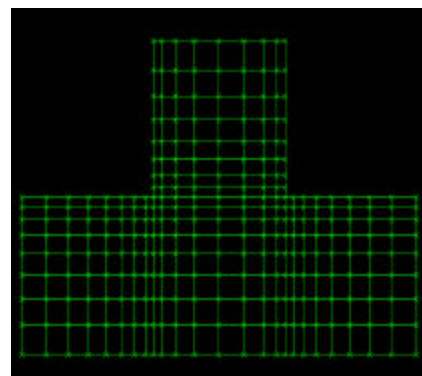


FIGURE 8
SIDE ELEVATION OF MODEL AFTER MESH REFINEMENT.

Loading and Boundary Conditions

The assumed actual uniform static load on the test part is 1000 lb. The uniform static load is acting on the left vertical surface of the step with the whole base of the sample part fully fixed. An example source of the uniform static load can be from a mating part acting on the surface. A base frame that is required to support a dead weight which is essentially constant overtime, and the base frame does not move can be a good example (Refer Figure 9).

The vector of the loading conditions and specified boundary conditions are shown in Figure 10. The direction of uniform static load is represented by the horizontal arrows and the fixed base boundary conditions are represented by the triangles at the base of the part as shown in Figure 10.

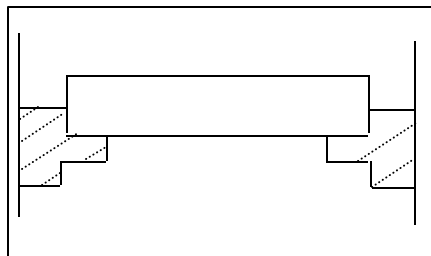


FIGURE 9
LOAD SOURCE AND APPLICATION EXAMPLE

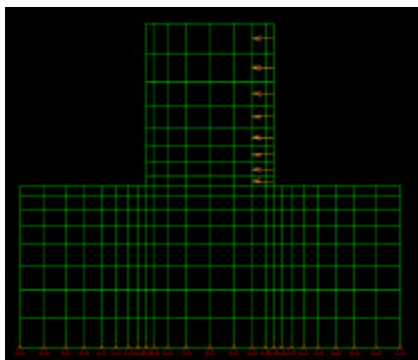


FIGURE 10
LOADING AND BOUNDARY CONDITIONS FROM SIDE ELEVATION.

Material Properties

In this research, Aluminum Alloy (Aluminum Association Number 2024 - O) is selected as the material for the sample part. This aluminum alloy is easily machined and considering the cost and strength of aluminum alloys, they are among the most versatile materials from the standpoint of fabrication. The table of materials properties shown in Table I provides the required data for conducting engineering analysis.

TABLE I
MATERIAL PROPERTIES OF ALUMINUM ALLOY
[ASM METALS REFERENCE BOOK].

Material	Aluminum
Aluminum Association Number	2024
Modulus of elasticity E, Mpsi	10.3
Modulus of rigidity G, Mpsi	3.85
Poisson's ratio ν	0.33
Density d , lb/in ³	0.10
Yield strength S_y , kpsi	11.0

Testing and Results

Once the finite element model is completed with loading and boundary conditions, a test run is executed to analyze the stress concentrations and deflection on the sample part. The actual engineering analysis is conducted on the Algor finite element system. The output of the linear stress analysis and deflection is reported in a dithered plot of the stress and deflection of the sample part. A dithered plot is a graphical display of the stress variation in the form of colored areas. Dithered plots provide a vivid and impressive presentation of stresses and deflection as shown in Figures 11 and 12. The maximum stress and deflection under 1000 lb. is 7216.38 psi and 3.5e-4 in. respectively.

Safety Factor and Failure Criteria

A safety factor is a unitless ratio that is necessary to calculate and estimate the likelihood of failure. In engineering design the ratio is usually between yield strength/stress output, both having the same units of pound per square inch (psi). Other acceptable ratios include critical load/applied load and load-to-fail part/expected service load. In this research, the safety factor selected is between yield strength/stress output since they are a function of the applied loads and the part's geometry.

Several theories exist in explaining failure, but the most accurate approach that agrees closely with experimental data is the *von Mises* theory [Norton; 1996]. This theory is the best choice for predicting failure in the case of static loading of ductile material in which the tensile and compressive strength are equal. The *von Mises* theory was adopted in this research. The direct comparison of the von Mises stress with yield stress allows identification of areas that have yielded.

Considering the safety factor of $N = 3$, the calculation so that the stress state will be safely inside the failure-stress value:

$$N = \frac{S_y}{S'} \tag{1}$$

$$S' = \frac{11000}{3} = 3666.67 \text{ psi. (Threshold stress value)}$$

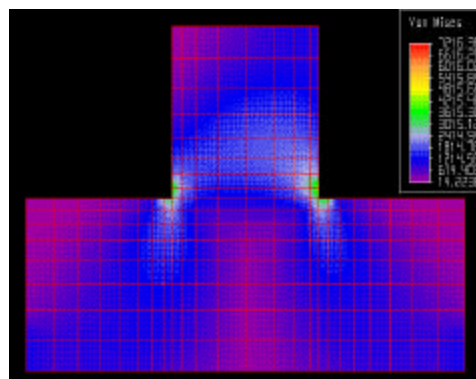


FIGURE 11
SIDE VIEW OF STRESS CONCENTRATION AT 1000 LB.

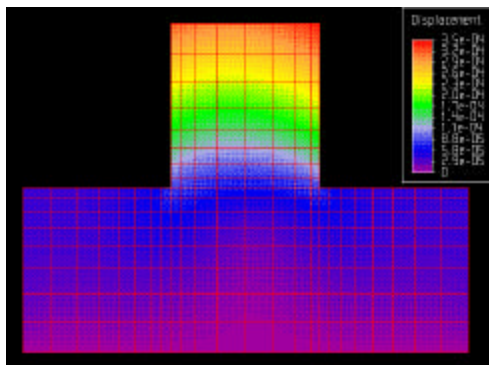


FIGURE 12
SIDE VIEW OF DEFLECTION AT 1000 LB.

Critical performance information regarding the linear stress and deflection data is collected. This data is compared to the known calculated threshold stress value of 3666.67 psi. Any value exceeding the yield stress is an indication that the part has yielded under that particular loading condition.

Data Analysis and Design Modification

Under the assumed load of 1000 pounds, peak stress is located at the corners between the coplanar surfaces as shown in Figure 11. Although considerable small deflection occurs, 3.5e-4 inch, the stress output is found to be 7216.38 psi. This value is well beyond the specified threshold value of 3666.67 psi. Design modification is conducted by generating a sharp fillet with radius R_i between coplanar surfaces. The highest sharpness of fillet (H_i / R_i) value of 6.0 is selected.

$$\text{Sharpness of Fillet: } 6.0 \geq [H_i / R_i] > 1.0$$

$$H_i / R_i = 6.0$$

$$R_i = 0.5 / 6.0 = 0.0833 \text{ inch.}$$

A fillet with a 0.0833 inch radius is introduced to the test part, stress and deflection are again analyzed. Under the same loading and boundary conditions the test data collected shows a maximum stress output of 4937.88 psi and maximum deflection of 2.5e-4 in. The mating part forcing on the test part is assumed to have the equivalent fillet radius.

The element shape selected for most parts of the model is a solid or brick element, while the region with fillet are assigned with hexahedron elements. As previously, the element aspect ratio is again kept under 3 for stress analysis.

Figure 13A and 13B show the dithered plot of the stress on the test part under a 1000 pound load.

The analysis result shows that the maximum stress output of 4937.88 psi exceeded the safety threshold value of 3666.67 psi calculated for load of 1000 lb. Further iterations of design modification is conducted by reducing the sharpness of fillet until the stress output is equal or lower than the threshold stress value as shown in Table II.

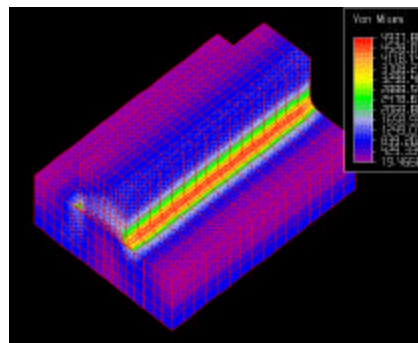


FIGURE 13A
3D DITHERED PLOT OF STRESS WITH 6.0 SHARPNESS OF FILLET.

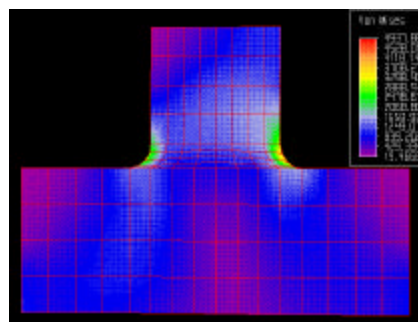


FIGURE 13B
SIDE VIEW DITHERED PLOT OF STRESS.

TABLE II
DEFLECTION AND STRESS OUTPUT FOR VARIOUS DESIGN ITERATIONS.

Iterat -ions	Fillet Sharpness	Fillet Radius (in)	Max. Deflect'n (in)	Max. Stress (psi)	Threshold Value, Psi
1	-	-	3.5e4	7216.3	> 3666.67
2	6.0	0.0833	2.5e-4	4937.8	> 3666.67
3	5.0	0.1000	2.4e-4	4599.3	> 3666.67
4	4.0	0.1250	2.3e-4	4132.3	> 3666.67
5	3.0	0.1670	2.0e-4	3736.9	> 3666.67
6	2.5	0.2000	1.8e-4	3170.4	< 3666.67

Figure 14A and 14B show the dithered plot of the stress on the test part under a 1000 pound load.

Under the load of 1000 pounds, the test results identified that the maximum stress output on the test part with a sharp fillet of 0.2 inchs is 3170.40 psi and a minimal deflection of 0.00018 inchs. Comparing the stress value with the specified threshold value of 3666.67 psi, it is within the safety range.

Thus, it can be concluded that it is highly unlikely for the improved design test part to fail by yielding or breaking under the assumed conditions. Even though a lower stress output can be obtained by further modification with a full fillet, this design is unsuitable given the load position, also the design with a sharp fillet had achieved the target.

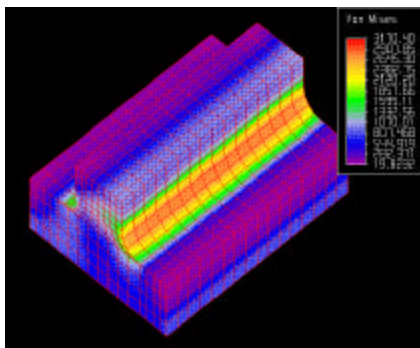


FIGURE 14A
3D DITHERED PLOT OF STRESS WITH 2.5 SHARP FILLET.

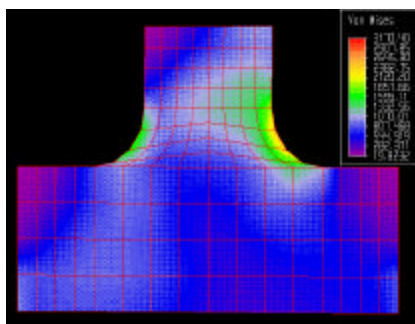


FIGURE 14B
SIDE VIEW OF STRESS PLOT WITH 2.5 SHARPNESS OF FILLET.

The improved design of the test part, shown in Figure 15, can then be transferred to a CAD/CAM system using either data exchange format (DXF) or initial graphic interchange specification (IGES) format for toolpath generation. The NC codes generated from the CAD/CAM system can be downloaded onto a numerical control machine for the production of the improved part.

Summary of Research Work

The objectives of this research were to integrate analysis and design improvement in a reverse engineering framework by further utilizing the geometric data acquired through the contact digitizing method of a CMM. Critical performance information of a part to be reverse engineered was sought without conducting costly destructive or non-destructive testing of the part. Instead, the critical performance information was acquired by conducting engineering analysis on the generated CAD model.

To accomplish these objectives the wire-frame model generated in the modeling module based on the digitized data of the test part is transformed into a finite element model. The finite element representation of the test part is input to a finite element analysis system, which, based on the provided loading and boundary conditions, generates the stress and deflection data on the test part. The generated test data on stress is compared to the calculated threshold stress value, which incorporates a safety factor. Design

improvement on the test part is executed and tested until a suitable and improved design is accomplished.

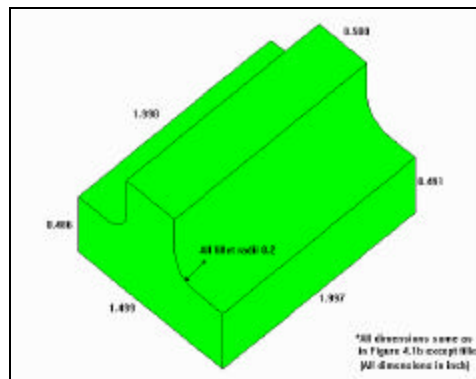


FIGURE 15
PARTIALLY DIMENSIONED DRAWING OF MODIFIED PART.

CONCLUSIONS

By providing the design engineer with the NRES, the task of reverse engineering an existing part and producing an improved and superior part is greatly simplified and structured. It is very easy for the engineer or designer to analyze and predict the performance of the part instead of merely reproducing a clone of the existing part. Changes in the component or part design can be conducted with ease and engineering analysis can predict how the changes would affect factors such as stress and deflection. This eliminates the need for conducting costly and time consuming destructive or non-destructive testing on the part. Instead of reverse engineering a part that might have failed due to inferior design, the design engineer has the capability of producing a superior designed part.

Past research and development in the area of reverse engineering has contributed tremendously to tasks such as contact data acquisition, non-contact data acquisition, and integrating computer-aided design and computer-aided manufacturing. This research has integrated analysis and design improvement in the reverse engineering framework to assist in the task of generating performance information and design improvement procedures for a prismatic part. This area of reverse engineering will help reduce manufacturing lead time and promote consistency in integration of design and engineering analysis in the reverse engineering framework.

The publication of this research work will provide engineering students the larger perspective of reverse engineering. It encompasses from initial data acquisition, CAD model generation and finite element analysis before the part is re-manufactured.

The prototype new reverse engineering system developed in this research has the following limitations:

- the test part is limited to a prismatic part with planar surfaces.
- the workpiece material is limited to ductile materials with no crack formation.
- only static loading conditions are considered.
- only room-ambient environment are considered.

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