PROPELLER-WASH INDUCED EROSION AND METHOD FOR ITS PREDICTION

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SUMMARY

This experimental research has been carried out with a view to investigate scouring action of a propeller wash in an open water situation. The dependency of scouring process with respect to time is considered. The experimental coefficients are related to propeller and sediment characteristics. They are also correlated to each other. A semi-empirical relationship is established to predict maximum scour depth with respect to time.

INTRODUCTION

The design of a propeller in relation to the performance of a ship has long been a matter of great interest, but the study of the characteristics of the wash produced, and its erosive power, was only recently given consideration.

Propeller-wash induced erosion in itself is not necessarily serious if it occurs well away- from the harbour structures and the resulting eroded material is not deposited so as to reduce the waterway's navigable depth. However, since the source of scour is the screw wash of ships manoeuvring at or near a berth, it is most likely that it may undermine the nearest foundation. This can affect the stability of the structure which ultimately may lead to its failure.

The problems caused by the scouring action of the wash produced by a rotating propeller have become widespread. A number of authors have reported the damage resulting from the propulsion action of the ships.

McKillen [1] reported on the severe propeller jet induced damage at Lame harbour in Northern Ireland. A survey at one of the berths showed that scouring in the bed overlaid by 250mm diameter cobbles, was taking place at rate of 0.6m per year. When a protection in the form of .a concrete filled fabric mattress was provided, it was broken within a short period.

Diver inspections at port Elizabeth in South Africa showed that solid faced quay walls were subjected to damage caused by bow and stern thrusters, Chait[2]. He pointed out that damage could take place in two ways; either by the undermining of the quay wall foundation or by the disintegration of grout seals in joints between concrete sheet piles and/or caissons and the eventual leeching out of sand backfill, leading to a sinkhole in the quay surface. It was found at another berth that three caissons out of the five which make up the berth were undermined.

They found bed velocities in the range 3 to 4m/sec, with scour rates which could reach up to 0.5m per month.

Bergh and Cederwal [4] conducted a survey of Swedish harbours. They examined a total of eighteen quays. It was found that sixteen of them suffered 'propeller scour problems that required costly remedial work. A few years later another survey was conducted by Bergh and Magnusson[5]. This revealed that the number of quay structures seriously damaged increased to 25 with extensive recurrent refill of erosion pits and/or dredging going on in about 10 harbours. .

The erosion of bed sediments can cause environmental deterioration. Clausner and Truitt[6] highlighted the propeller wash effects on protective armour layer for Contained Aquatic Disposal sites.

Since bed erosion can influence the stability of a harbour structure, an efficient means of predicting the scouring process before hand becomes essential. This would enable measures to be provided to encounter the problem at design stage. Propeller-wash induced erosion can be reduced or eliminated by a proper design of the berth structure which may include bed protection, and/or imposed operational constraints.

THEORETICAL BACKGROUND

No detailed work on scouring action of propeller jets was found prior to Hamill [7] and Stewart [8]. Most of the work was related to bed protection material although a limited amount of experimental work had been carried out related to propeller induced sediment movement. The main papers related to this problem were written by Robakiewrcz [9], Romisch [10], Blaauw. and van de Kaa [11], Bergh and Cederwall[14], Verhey[12] and Prosser [13].

Sleigh [14], however, investigated in detail the erosion of side slopes by propeller action caused by vessels during manoeuvring operations.

Rajaratnum [15] found for circular submerged jets that maximum scour depth is a function of densimetric Froude's number. Verhey[12] applied Rajaratnum's approach on plain jets and analyzed his experimental results from propeller wash induced erosion. He expressed maximum scour depth as a function of F_0 and derived the following equations, for the sediments within the range. 0.1 m < d_{50} < 0.3m,

$$\frac{\varepsilon_{\max}}{Z_b} = 4\times10^{-3}\left[\frac{F_0}{Z_b / D_0}\right]^{2.9} \qquad (1)$$

where D, is the initial diameter of the slipstream and Z,, is the distance between the jet axis and the bed,

Hamill[7] carried out detailed experimental work on the scouring action of the screw wash by using two propellers and two sediments. He proposed the following equation, similar to the equation developed by Verhey[12], to predict the maximum scour depth, for the sediments in the range 0.5mm < d_{50} < 2mm.

$$\frac{\varepsilon_{\max}}{Z_b} = 0.0467\left[\frac{F_o}{Z_b / D_p}\right]^{1.39} \qquad [2]$$

However, he pointed out that this equation provides only an estimate of the expected maximum scour depth. Hamill [7] established also a relationship for predicting maximum scour depth with respect to time

$$\varepsilon_{\max} = 45.04\Gamma^{6.98}\left[LN(t)\right]^{\Gamma} \qquad [3]$$

Where

$$\Gamma = 4.113\left[\frac{C}{d_{50}}\right]^{-0.742}\left[\frac{D_p}{d_{50}}\right]^{-0.522} F_o^{\;-0.652} \qquad [4]$$

He recommended the use of this equation for sediments in the range 0.5mm < d_{50} < 2mm.

Stewart[8] carried out a series of experiments and proposed a similar equation, as suggested by Hamill, but with different experimental coefficients. In the present investigation, it was decided to develop the equation for maximum scour depth with respect time on the basis of dimensional analysis, Hamill[7]

EXPERIMENTAL TECHNIQUE

All the sediment experiments were carried out in a waterproof tank having 5400mm x 3000mm sides, with 700mm depth, Hashmi [16]. The propellers were provided with a drive system and gearing arrangement.

A model analysis was carried out to determine the diameter of propellers, speed of rotation, clearance of propeller tip to sand bed, and size of .sediment to be used in the experiments. In this experimental study two sediments, three propeller tip to bed clearances and six propeller speeds were used.

Before starting each experiment, the sand bed was levelled by means of a straightedge pulled over two wooden runners placed across the propeller axial line at each end of the sand bed. The depth of the runners was fixed according to the required tip to bed clearance. This allowed the jet generated by the propeller to act on bed which was initially flat.

The development of the scour profiles was monitored at set time intervals, for each experiment, until approximately asymptotic conditions were reached or erosion was measurably ceased. As the rate of scour decreased with time, the initial time periods between measurements were short. Successive time intervals were doubled starting at 10 seconds. After each interval, the jet was stopped and profiles of the resulting scour hole were determined along propeller cetreline, see fig.1.

Readings were taken at 50mm intervals along each profile. Once the scour had measurably ceased, or the profile reached an asymptotic state, the measurements over the entire pit were taken on 50mm grid.

ANALYSIS OF RESULTS

An equation for predicting the maximum unconfined scour depth at any interval of time was developed by Hamill[7]. Stewart[8] established a similar relationship with different experiment coefficients. This equation is valid in the range of his experiments only. In order to make it widely applicable, i.e., for any propeller or sediment, it was required to be refined. In the present investigation, quite different combination of propellers, sands, propeller rotational speeds and bed clearances were used. It was, therefore, decided to improve the equation for maximum unconfined scour depth. Hamill[7] and Stewart[8] permitted their results to be used for this objective. All the data based on four propellers of widely varying characteristics, with three different sediments ranging from medium sand to fine gravel, sizes varying from 0.5mm to 4mm, were accumulated. These results were manipulated to establish an overall equation which would be valid for any propeller acting on a range of sediments to predict maximum scour depth in an unconfined situation of a ship's screw wash. Thus the maximum unconfined scour depths caused by twenty one jets corresponding to twenty one speeds of rotation of propeller with nine propeller tip to bed clearances were investigated. For each test, the following type of equation was obtained, see Fig.2,

$$\varepsilon_{mu} = \Omega\left[LN(t)\right]^{\Gamma} \qquad [5]$$

On the basis of the dimensional relationship,

$$\frac{\varepsilon_{mc}}{D_p} = f\left|\frac{C}{d_{50}}, \frac{D_p}{d_{50}}, F_o\right| \qquad [6]$$

A geometric multiple regression analysis was carried out and the following equation was developed for Γ,

$$\Gamma = 2.093\left(\frac{C}{d_{50}}\right)^{0.731}, \left(\frac{D_p}{d_{50}}\right)^{-0.430} (F_o)^{-0.563} \qquad [7]$$

With an R^2 value of 0.83, a best fit statistic of 82 and 68 % of the data lay within +16.6 % and -14.23 % of the predicted values using the equation

Similarly, the geometric multiple regression analysis yielded the following equation to predict the Ω values

$$\Omega = 0.078\left(\frac{C}{d_{50}}\right)^{-4.58} \left(\frac{D_p}{d_{50}}\right)^{2.94} (F_o)^{3.78} \qquad [8]$$

With an R^2 value of 0.80, a best fit statistic of 79.51 and 68 % of the data lay within + 95 % and -66 % of the predicted values using the equation.

A relationship between Ω and Γ was also established, as follows:

$$\Omega = 39.67\Gamma^{-6.30} \qquad [9]$$

Which explained 92.5 % of the variations in the data, with a best fit statistic of 72 and 6S % of the experimental data lying within +10.29% and -9.33% of the predicted values using the equation. The equation is shown plotted in Fig.3. It can be observed that the equation represents the data quite well.

It was found that the equation for Γ had a better correlation with the experimental data than that for Ω. Thus the final form of the formula to predict the unconfined scour depth at any interval of time was obtained in terms of Γ

$$\varepsilon_{mu} = 39.67\Gamma^{-6.30}\left[LN(t)\right]^{\Gamma} \qquad [10]$$

Where Γ can be determined by the equation [7].

It was quite interesting to compare the existing equation [11] proposed by Stewart[8] for predicting Γ as shown in Fig.4.

$$\Gamma = \left(\frac{C}{d_{50}}\right)^{0.94}\left(\frac{D_p}{d_{50}}\right)^{-0.4757}(F_o)^{-0.5256} \qquad [11]$$

With the proposed equation [7] for predicting the Γ values as shown in Fig.5. It can be observed that the measured data is more scattered around the existing equation line than that about the proposed curve. Thus the proposed equation has a better correlation with Γ values. This is because it was derived from all the results of Hamill [7] Stewart[8] and from the present investigation, i.e., it is based on the data with a comparatively larger variety of combination of various experimental parameters involved.

CONCLUDING COMMENTS

This experimental investigation was undertaken to understand the scouring action of propeller wash behind slowly manoeuvring ships. The analysis of each sediment test revealed the following:

The development of maximum scour depth is proportional to natural logarithm of time. The experimental coefficients were found to be well related to the propeller and sediment characteristics. They were found also to be highly correlated to each other.

The time dependent equation for predicting the maximum unconfined scour depth at any time interval has been refined. This relationship was based on the data from four different propellers of widely varying characteristics and three different sediments ranging from medium sand to fine gravel. The proposed formula has been found to have much better correlation with the experimental coefficients than the existing one as it was derived from the results of tests with a comparatively larger variety of combination of the various experimental parameters involved.

ACKNOWLEDGEMENT

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NOTATION

F_o Densimetric Froude number where

$$F_o = V_o / \sqrt{[gxd_{50} x\{(\rho_s - \rho)/\rho)]}$$

g Acceleration due to gravity

D_o Initial diameter of propeller

V_o Efflux velocity

Z_b Distance between jet axis and bed

ε_{max} Maximum scour depth

C Tip clearance ratio

ε_{mu} Maximum unconfined scour depth

Γ, Ω Experimental constants

d_{50} Average sediment grain size

D_p Propeller diameter

t Time

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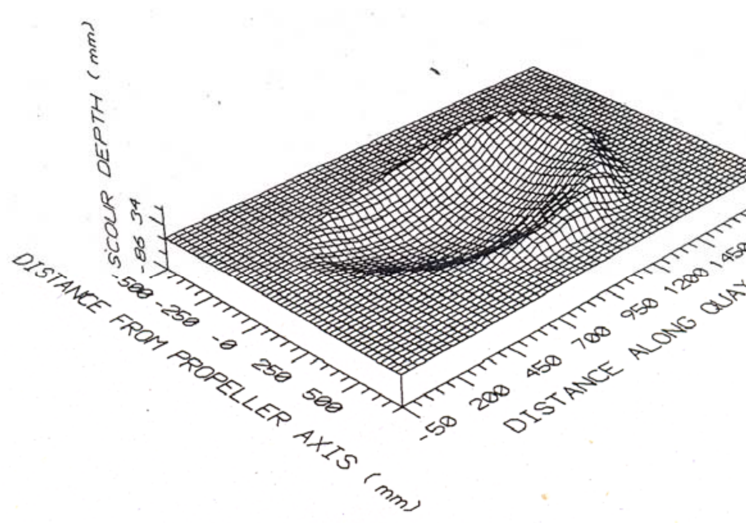

FIG.1. ISOMETRIC AND CONTOUR VIEWS OF EROSION PIT PRODUCED BY PROPELLER 76 ACTING ON FINE GRAVEL

FOR TIP CLEARANCE RATIO OF 1.25

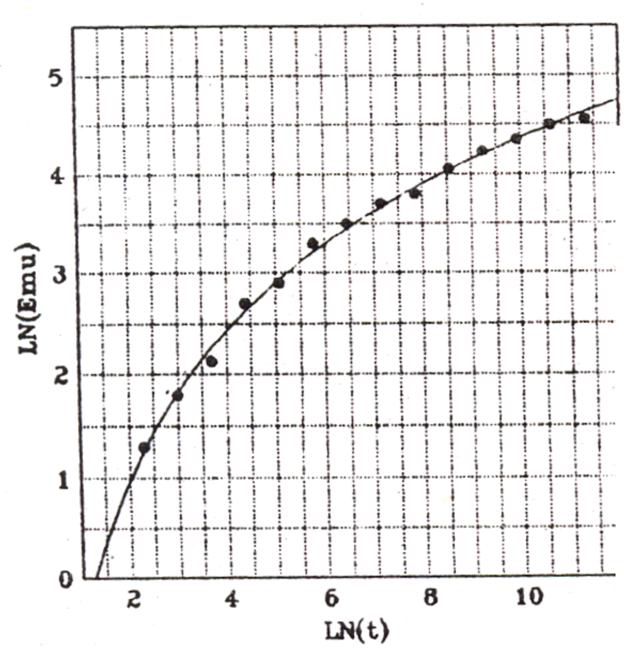

FIG.2. COMPARISON OF RATE OF DEVELOPMENT OF UNCONFINED SCOUR ALONG JET CENTRELINE FOR PROPELLER OF DIA.131MM. ROTATING AT 450 RPM

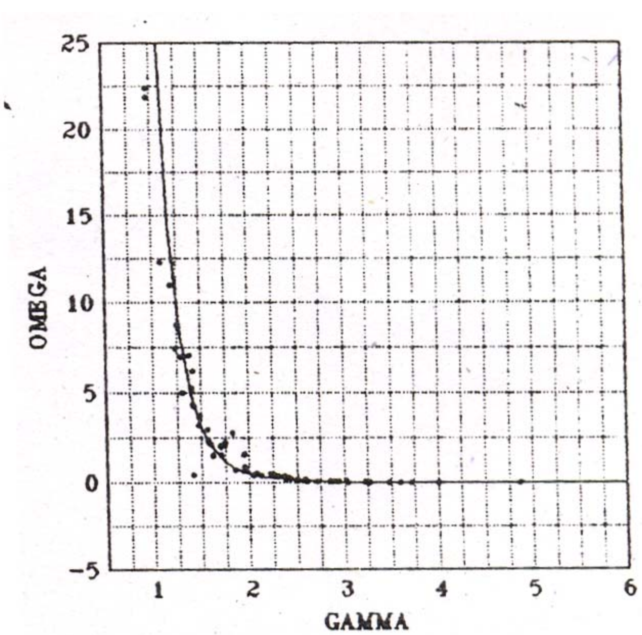

FIG.3. CORRELATION BETWEEN OMEGA AND GAMMA VALUES FOR UNCONFIND JET BY INCLUDING DATA FROM HAMILL[7] AND STEWART[8]

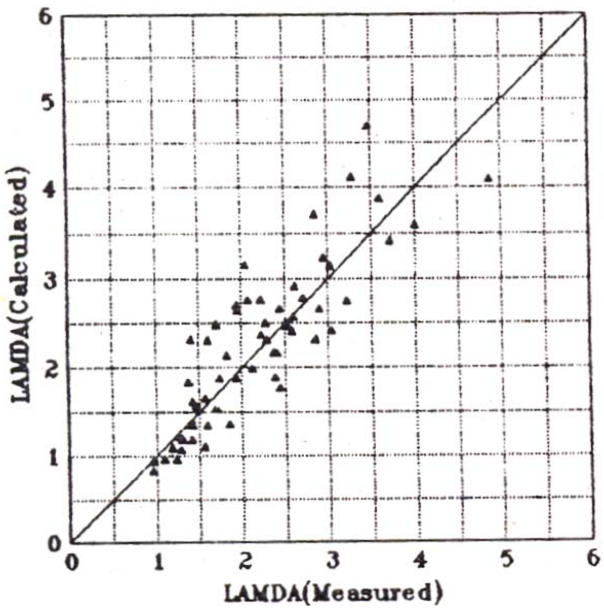

FIG.4. COMPARISON OF EXPERIMENTAL GAMMA VALUES WITH VALUES PREDICTED USING EQUATION [11] PROPOSED BY STEWART[8]

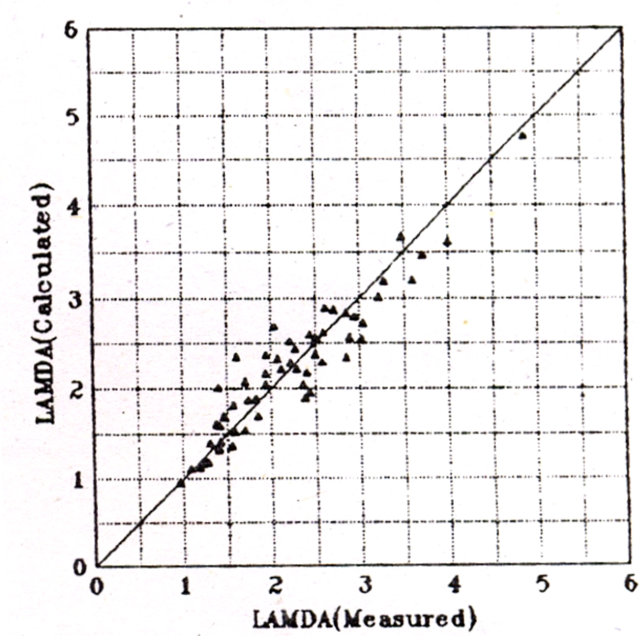

FIG.5. COMPARISON OF EXPERIMENTAL GAMMA VALUES WITH VALUES PREDICTED USING EQUATION [7] INCLUDING RESULTS OF HAMILL[7] STEWART[8]

EVALUATION OF FRACTURE TOUGHNESS OF GRAPHITE FIBER REINFORCED THERMOPLASTIC

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ABSTRACT

In the present analysis, fracture toughness parameters for graphite fiber reinforced thermoplastic have been evaluated according to the classical linear elastic fracture mechanics (LEFM) approach in which the critical stress intensity factor is determined. In order to assess the LEFM fracture parameters a series of experiments has been performed. The experimental fracture toughness tests were performed on compact tension and double edge notch bend test specimens. The results show the Graphite Fiber Reinforced Thermoplastic (GFRTP) to be much stronger than typical thermoplastic including recently developed high strength plastic products. The toughness parameters were seen to be only slightly sensitive to specimen geometry.

INTRODUCTION

Fiber reinforced injection molding thermoplastic compounds are often chosen to replace metal parts because of advantages in weight, corrosion resistance and lower fabrication cost. To achieve the strength performance requirements of the application, it is the fiber that provides the reinforcement to the composite. Carbon or Graphite fibers provide the highest reinforcement achievable on a commercial basis for thermoplastic composite. A reduction in toughness could diminish the durability of the thermoplastic composite part. Improved strength-to weight and stiffness-to-weight ratios are two main features of interest to design engineers in military/aerospace, sporting goods and industrial markets.

Electrical/Electronic engineers are attracted to the excellent wear properties of GFRTP and their electrical conductivity for dissipating static electricity, or providing EM I shielding.

A common engineering thermoplastic used for the above cited applications is nylon (polyamide), either type 6-6 ; 6 ; or 6-12 for low moisture applications. Nylon 6-6 is the most common of the three. The generic composition of our study is comprised of nylon 6-6 and thirty weight percent PAN graphite fibers.

Fracture toughness is represented by the symbol **Kc** and is the critical value of the stress intensity factor at a crack tip necessary to produce catastrophic failure under simple uniaxial loading. In general, the value of the fracture toughness is given by

$$K_c = y \quad \sigma_f \sqrt{\pi a}$$

Where

y = dimensionless geometry factor on the order of 1

$\boldsymbol{\sigma_f}$ = overall applied stress at failure.

a= the length of the surface crack.

It has units of Mpa $\sqrt{m}$

EXPERIMENTAL PROGRAM

Test specimens made from the macroscopically homogeneous GFRTP were interrogated in a series of laboratory experiments. The experiments conducted were design to determine the engineering properties of GFRTP and to evaluate its possible use as an engineering material. The results of the experimental program are presented herein. Particular attention was given to the measurement of the fracture characteristics of the composite. Specimens to be tested in tension, and fracture were machined from samples of either 3, 5 or 10 mm thickness. The procedure chosen for the measurement of the engineering properties of the GFRTP were in accordance with the American Society for Testing and Materials (ASTM) standards for the testing of rigid plastics. Early in the laboratory program it became clear that the engineering properties of the GFRTP were directionally dependent. Therefore, the results of the tests will be presented in terms of X and Y directions corresponding to the directions parallel and transverse to the direction of rolling.

The tensile properties of the composite were evaluated by performing uniaxial tension tests according to ASTM Standards D-368 [1]. Strain gages applied both parallel and perpendicular to the loading axis provided an accurate measure of the stress strain behavior as well as Poisson's ratio for each specimen. A typical stress-strain curve is shown in Fig.1. The average ultimate tensile strength and elastic modulus were determined to be 74 MPa and 100 MPa respectively.

According to ASTM Standards E-399 [2]. The fracture toughness testing to obtain a critical plane strain stress intensity factor **Kc** , was carried out. The two specimen types tested were the Compact Tension (CT) and the Double Edge Notch Beam (DENB) specimens. The sizes of these specimens as tested are given in Fig.2. The depth of the starter notch was varied in the DENB samples to evaluate notch depth sensitivity. The load-displacement record for the DENB specimens was obtained as specified in ASTM test E-813-82 [3]. The loading rates for the CT and the DENB specimens varied depending upon the depth of the starter crack. Fracture toughness values for the two specimen types are presented in Table-1, as are typical for a variety of structural materials.

The ASTM test standards E-399, requires that all test specimens have closed sharp cracks existing ahead of the machined starter notch to accurately measure LEFM parameters. In an attempt to generate such a crack, several CT and DENB specimens were loaded in the manner prescribed for fatigue pre cracking. Once cracked, failure followed at a very rapid rate, and none of the specimens prepared in this way could be unloaded before the crack extended through the full specimen width. Fatigue cycling of additional CT specimens was attempted using different loading parameters. These attempt typically resulted in similar failures. Comparing this range of apparent fracture toughness values with published values considered to be representative for similar materials (Table-1), shows the GFRTP toughness to be somewhat high. Since the measured toughness would be higher than the true toughness for all crack radii greater than the critical radius, the data indicate the possibility that the notch radius affected the toughness measurements. The average tip radius for these specimens was found to be 0.042 mm. In order to determine whether the measured toughness of GFRTP specimens was in fact sensitive to the machined radius, a second set of tests was conducted on 3 mm DENB specimens with varying radii at the notch tip.

Buresch [4] had shown in experiments performed on alumina that a linear relationship existed between the apparent fracture toughness **Ka** and the square root of the notch root radius. He further observed that below a certain limiting value of the root radius, the apparent toughness was equal to the true toughness. By loading each specimen to failure and plotting apparent critical stress intensity factor as a function of notch root radius a behavior similar to that observed by Buresch for alumina can be seen to exist for the GFRTP, Fig.3.

One of the requirement of ASTM E-399 is that plane strain conditions exist through the thickness of the specimen at the crack front. According to the standard the minimum specimen thickness, B, is equal to 2.5 **(Kc/σys)** .For a conservative estimate for **Kc** and strength, the minimum thickness was found to be 2.5 mm. Modeer [5] however has proposed a minimum thickness equal to four times the ASTM E-399 recommended minimum value for plastic materials. Using Modeer's recommendations for a minimum thickness, plane conditions can be assumed to exist when specimen thickness is at least 10 mm. In Fig.4, **Kc** has been plotted for varying thickness and orientation of the specimen. The GFRTP can be seen to behave approximately as predicted by Modeer.

The results of the tests on the 10 mm thick specimens with different crack length can be investigated to determine whether the GFRTP is notch sensitive or not. A material is said to be notch sensitive if the net section stress is affected by the crack length. It can be shown that a material having constant **Kc** must be notch sensitive. Fig.5 shows the variation in apparent toughness as a function of notch depth for the 10 mm specimens.

CONCLUSION

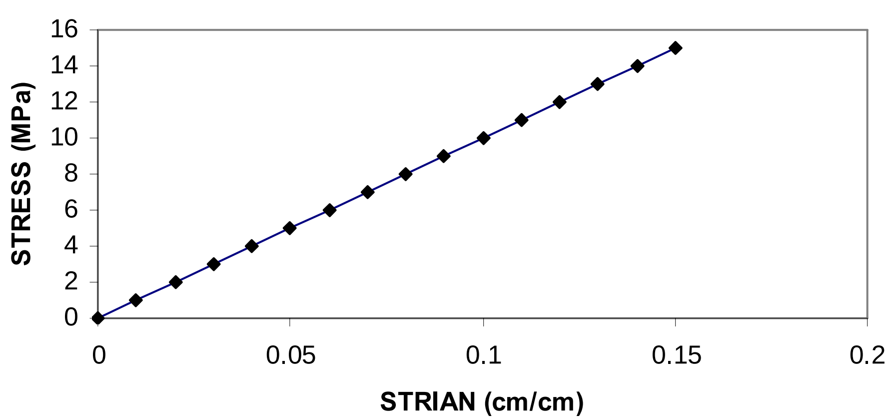
The results of the analysis show the GFRTP to be much stronger than typical industrial plastics available. The test results showed a minimum specimen thickness , notch sensitivity, and the effect on measured toughness of the material. The toughness parameters were seen to be slightly sensitive to specimen geometry. It has been shown that the fracture characteristics can be characterized by the fracture toughness parameter, **Kc** .

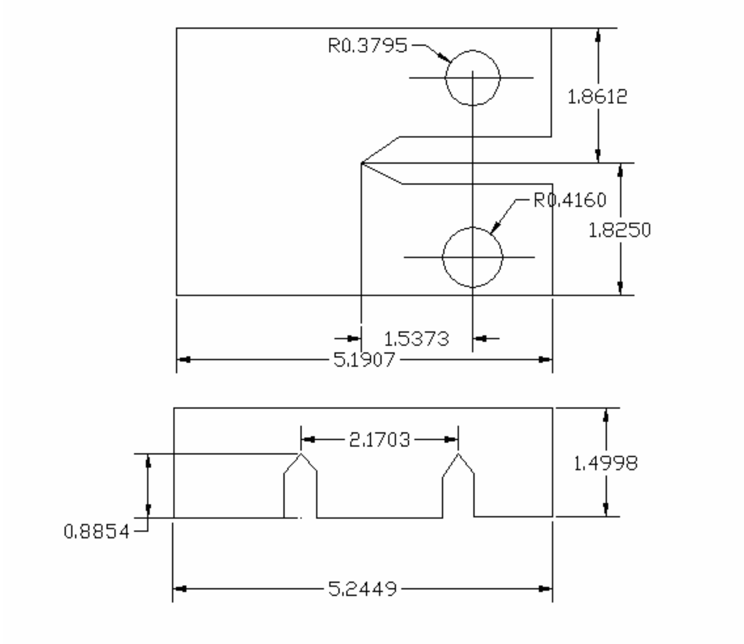
TABLE-1 FRACTURE TOUGHNESS VALUES

MATERIAL	K_c (MPa $\sqrt{m}$)
GFRTP	11.25
Polyethylene	2
Polypropylene	3
Polystyrene	2
Polyesters	0.5
Polyamids	3
Epoxies	0.3-0.5

Source: R.A.Flinn and PKTrojan, "Engg. Materials and their applications, 2nd edition. Houghton Mifflin Company, Boston. 1991

Fig.1 STRESS-STRAIN CURVES




R0.3795
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R0.4160
1.8250
1.5373
5.1907
2.1703
1.4998
0.8854
5.2449

Fig 2

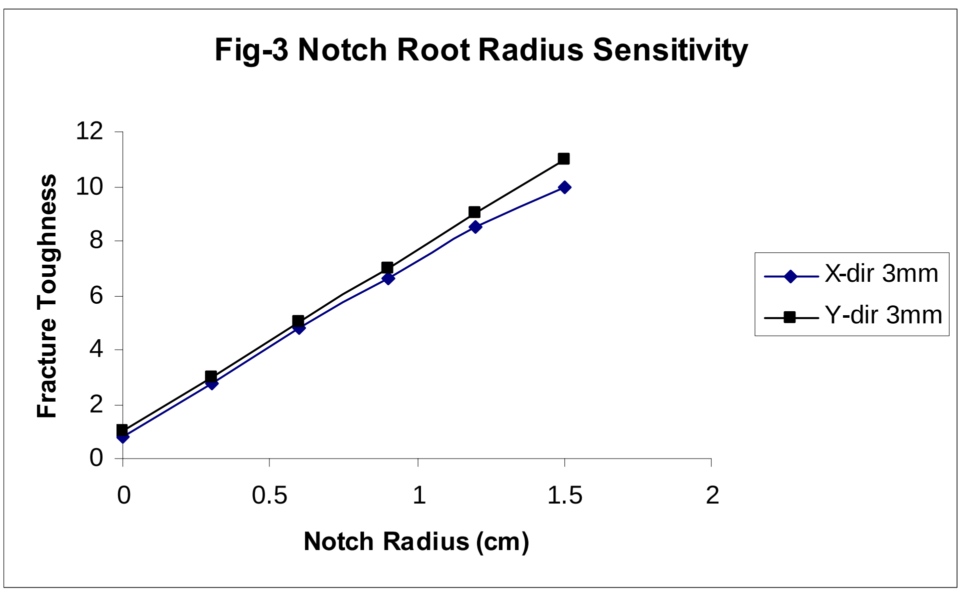


Fig-3 Notch Root Radius Sensitivity
Fracture Toughness
Notch Radius (cm)
X-dir 3mm
Y-dir 3mm
0
2
4
6
8
10
12
0.5
1
1.5
2

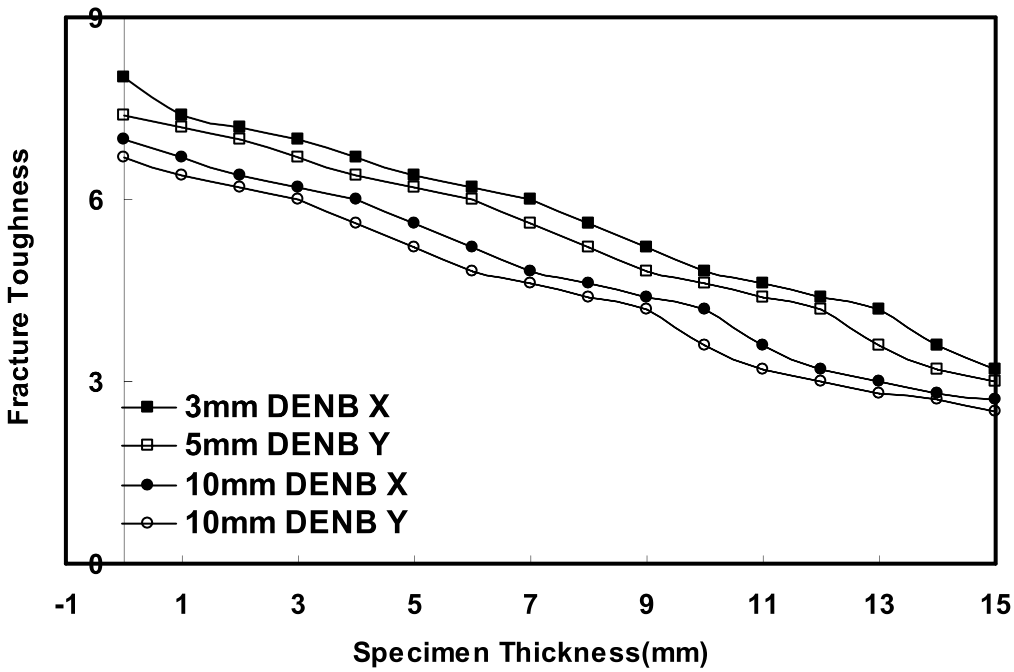
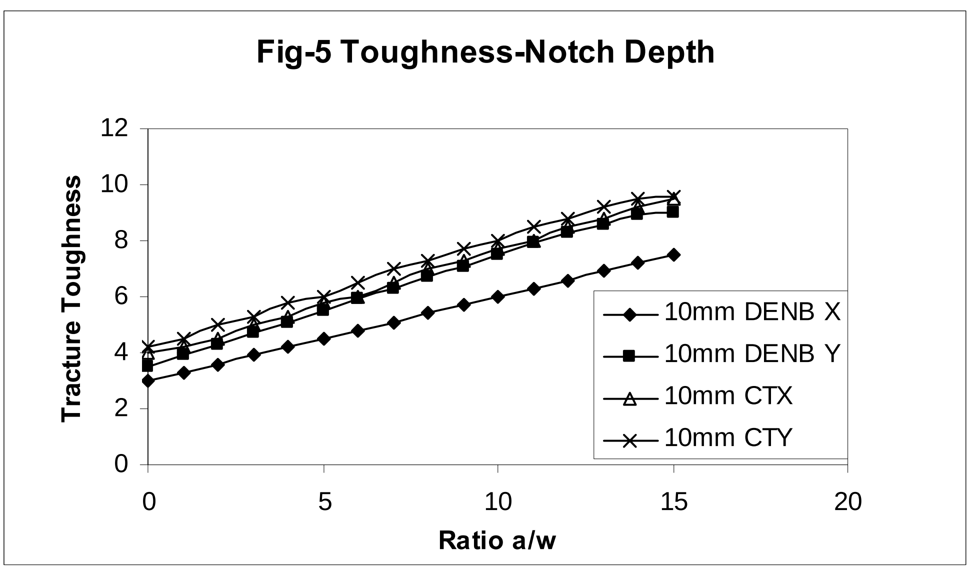


Fig. 4 Thickness-Toughness Curve



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