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Modified Center Interpolation Net for Classification of Composite Structures Tested Using Low Frequency Electronic Tapping

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Abstract: Problem statement: Most exhaustive NDT techniques require large capital equipment, are difficult to apply to complex geometric structures and, above all, are time-consuming to use and some take a considerable time to complete. As a solution to the problems associated with NDT applications, there is a need to establish an intelligent analysis system that supports a portable testing environment, which allows various types of inputs and provides sufficient data regarding damage severity in the tested structure. **Approach:** This research investigated possible fast NDT systems and algorithms and provides a novel approach that allows engineers and researchers to pinpoint defects in real time. The system was based on incident signals on a composite surface being detected and analyzed. Any damage in the composite causes a change in the detected signal. The proposed technique is suitable for high volume monitoring and inspection of safety critical components non-destructively. It unified through conversion the extracted information from irrelevant background using the developed Classification Algorithm with the ability to correlate obtained data to level of damage and it is effect on the structure overall performance. **Results:** The feasibility of using time measurements to establish the integrity of RIM composites using a handheld, low frequency, electronic tapping device has been studied. The relationship between damage and component thickness had also been established. **Conclusion:** A mathematical model describing the composite time response and its relation to both level of damage and tensile strength was presented. An excellent agreement between the model and the testing data was observed. Also the credibility of the measuring device and its promising future as a cheap on line NDT testing instrument was proved.

Key words: Low frequency, NDT, composites, impact damage, algorithm, modeling, tapping, classification

INTRODUCTION

The layered composites are presently the most widespread advanced materials in use. Among them, fiber reinforced composites with polymeric matrices (FRP or laminates) and polymeric sandwich materials, with thin laminate faces and foam or impregnated cores. Fiber reinforced composites provide unlimited alternatives, where the performance of the whole is superior to the sum of the parts.

The light weight, very strong and stiff fibers combined with weak and brittle matrix provide a wide range of material combinations with an opportunity for optimization that goes beyond mechanical properties to thermal, acoustic, electromagnetic characteristics.

The structural design and maintenance of composite structures involving these materials need comprehensive evaluation and characterization of mechanical properties and behavior under different loading conditions, in both undamaged and damaged states (Tohgo *et al.*, 2009; Mouritz *et al.*, 2009; Li *et al.*, 2009; Breitzman *et al.*, 2009; Kim *et al.*, 2009).

The complex nature of fiber reinforced composites makes them particularly difficult to test for defects. The use of composites in demanding applications like automotive and aerospace industries means, however, that it is particularly important to find the best testing methods. The increase use of these materials is expected to continue because they offer the designer, amongst other things, high specific strength and stiffness, increased design flexibility and excellent fatigue resistance.

As composite materials are finding increasing use in more demanding applications, requiring a high degree of accuracy and reliability, considerable effort is being made to define and setup quality control procedures and inspection methods.

Controlling the quality of raw composite materials is carried out to detect the following:

- Excessive void contents or porosity
- Contamination or foreign particle inclusions

- Variation in the degree of resin cure
- Inconsistent fiber volume fraction
- Dimensional inaccuracies
- Poor fiber-matrix bonding
- Broken or damaged fibers

A composite structure may also be damaged in service due to physical damage such as impact or fatigue creep. The influence of the environment on a structure due to ingress or moisture, exposure to hot and wet conditions for over long periods, contamination from oils or fluids may also cause damage, like surface abrasion and dents, delamination, fiber crack, bonding failure.

Such defects are all potentially detrimental to the mechanical integrity and consequently to the structural performance of a component. The extent to which a defect will affect the performance will depend on the geometry of the structure, the location and orientation of the defect, the type of applied stress field and the working environment.

In this study excitation at each testing point using the tapping technique has been successfully used. The study is carried out by means of employing an electronic tap tester that comprises both a transmitter which is equivalent to the tapping coin and a receiver both in one compact unit. Data interpretation and damage classification is done using a specially developed algorithm.

Impact damage: All structures from aircraft fuselages to chemical storage tanks will inevitably be subjected impacts of some type. Traditional laminated composites, however, perform very poorly when subjected to transverse impacts. It is therefore essential to understand the impact behavior of composites in order to properly design them.

The subject of composite impact behavior is one of enormous complexity. A single impact event can produce several different damage modes simultaneously. These damage modes are affected by the properties of both the impactor and the laminate.

Confidence in the application of safety critical structural composites in vehicles would be improved if a fast accurate method of assessing manufacturing flaws and service damage in relation to the structural engineering performance was available. A perceived problem with composite structures is that internal damage may seriously weaken a structure yet be undetected due to little surface evidence.

Structural damage of composites as a result of impact is regarded as one of the most critical aspects that restrict wider applications. In composites, the possibility of plastic deformation is limited which can lead to substantial amount of deformation upon impact.

At impact, a stress field is established within the composite structure, releasing a series of stress waves propagating through the material which initiates number of damage mechanisms that could cause splitting, de-bonding, matrix cracking, fiber pull-out, fiber breakage and delamination. The extent to which a specific failure mechanism affects the structure depends on the fiber, matrix and their inter-phase properties as well as the geometric form and fiber arrangements.

When a structure is tapped producing a sound, vibration at the major frequency modes of the structure at its fundamental values provides a way of characterizing the composite properties. These structural characteristics are essentially independent of position of excitation. When a structure is tapped, the characteristics of the impact are dependent on the local flexibility of the structure and the device used to strike it. Damage such as delamination results in a local increase in the structural flexibility, hence a change in the nature of the impact. The impact over a good area is found to be more intense and of shorter duration than that on a damaged area.

The difference in sound produced is due to the frequency content of the force pulse. The amplitude of the force input to the damaged area was found to fall rapidly with frequency. This means that the impact on the defective area will not excite the higher structural modes as strongly as the impact on the good zone. Therefore, the sound produced does not contain the higher frequencies and the structure sounds duller.

The change in the impact characteristic over a defect may be explained by considering the effect of the defect on the motion of the impactor. In the region of delamination, the flexibility of the structure in the direction normal to the surface is increased. This means that when an impactor strikes the structure above the defect, the surface “offers” more than over a good area. The damping effect also means that the impactor stays in contact with the surface for longer which results in a longer impact duration. Over a good area, the impact duration is controlled by the contact stiffness between the impactor and the structure. A delamination effectively reduces the contact stiffness.

Impact is a key issue in the design of composite structures where the impact event and extent are of importance. Damage occurs progressively during an impact and is a function of the impact event and structure resistance that is affected by material properties. Local and global effects need to be considered which gives an indication regarding the structure dynamic response. Method of impacting is also a factor where supported frames respond differently to impact compared to unsupported ones, indicating that boundary conditions significantly affect structure response and extent of damage.

The application of an impact can result in a dynamic stress which when established can induce a damage that propagates at a number of sites within the material thickness. Composites with their low transverse tensile strength can be prone to this type of effect.

Under normal conditions, material constituents in a structure are bound to their respective potential levels with relative stability. As impact energy is applied, shock waves (impulses) may cause damage such as fiber breakage or cracks (that can propagate over time). When a defect is induced, the original energy distribution would be affected, hence, new energy levels and pockets of energy sub-levels will be formed. This energy re-mapping can be correlated to the applied force of impact and classified through our developed system (David, 2008; Hayman, 2007; Stoika *et al*., 2009; Zangani *et al*., 2007; Williams *et al*., 2008; Zhang and Richardson, 2004).

MATERIALS AND METHODS

The test plaques were produced using the following resin and glass materials:

- A 1153/72/A Epoxy Resin with service record of in-durability supplied by Shell
- A 1153/172/B Hardner
- A U750/450 (Vetrotex) glass fibre (continuous fibre mat) with 7% thermo-plastic binder and random fibre orientation
- Release agent and film

The production process was carried out as follows:

- The cutting edges of the mould blades of the press machine are cleaned for effective glass fibre sizing
- The glass fibres are cut to 190×190 mm which fits the mould size on the pressing machine
- The glass fibre mat is cut to the required size after cleaning the machine to prevent contamination and facilitate trimming
- The top and bottom halves of the mould are brought together pneumatically with the bottom mould heating up the top mould to an equivalent temperature of about 100°C with heating time of about 35 min
- About 200 g of epoxy resin is placed in the oven which is set to between 70 and 80°C
- After heating, the epoxy resin is mixed with 50 g of hardener at 4: 1 ratio
- The top and bottom parts of the moulds are separated with release agent sprayed on their surfaces
- A release film is placed on the bottom mould with layers of glass fibre on the top of the film
- The mix of hardener and resin prepared earlier is deposited on the glass fibre layers
- The two moulds are brought together and left for approximately 5-10 min
- The finished component is then cured for 1 h

The produced components contained 5 layers of glass fibre with percentage volume fraction of 65.4 and 34.6 resin for 2 mm thickness and 10 layers of glass fibre with percentage volume fraction of 64.4 and 35.6 resin for 5 mm thickness.

Specimen were prepared and cut into rectangular shapes (130×150 mm). The composites were then subjected to impact loads using a drop weight system as shown in Fig. 1. The specimens were subjected to various levels of impact energy using 1.35 Kg dropped from various heights.

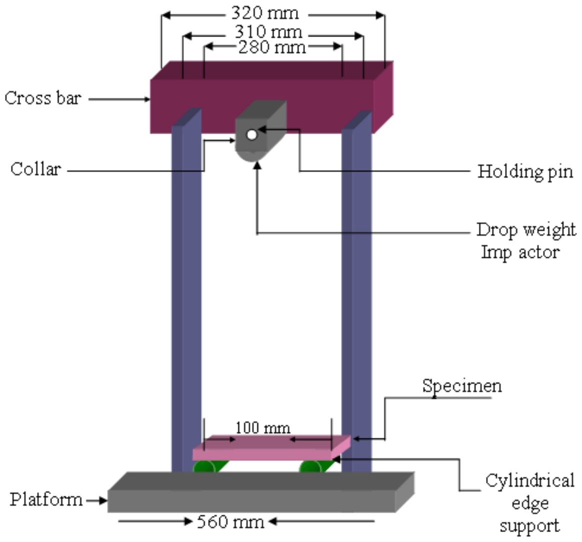

Fig. 1: Drop weight impact system

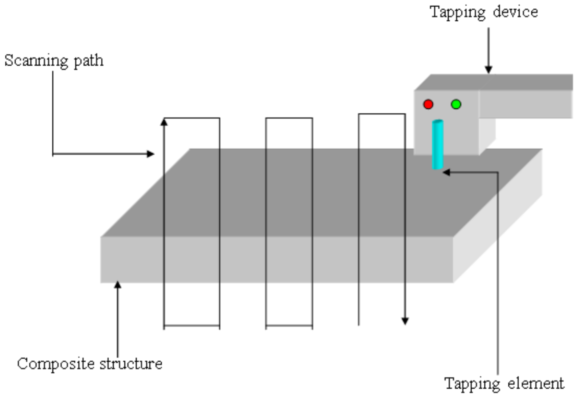

Fig. 2: Electronic tapping system

An electronic tapping instrument is used for damage detection as follows:

- A low frequency mode is selected before calibration with the number of averaged taps set to 8
- A reference value is obtained from both a known defect free part of the sample and a standard reference sample
- The device is then held vertically and the component is scanned left to right as shown in Fig. 2
- The data collected from the tests is downloaded into a PC for correlation, interpretation and classification

RESULTS

Tables 1 and 2 show obtained testing data for 5 and 2 mm RIM composite samples. Table 1 and 2 have data relating impact energy in Joules to the response factor K (Defect area time response to non defect area time response ratio), with Fig. 3 showing both responses. Table 3 and Fig. 4 show the relation ship between the response factor and measured tensile strength, while Table 4 shows response factor difference and impact energy of the tested RIM samples. Figure 5 shows how impact energy affected time responses of different composite thicknesses.

DISCUSSION

Low-energy impacts may induce localized damage in composites such as, fiber breaks, resin cracking, face sheet-core delamination, core crush, puncture, which is attributable to a number of fairly common discrete sources. Data interpretation and damage level classification is obtained through our developed algorithm which is based on the model shown in Fig. 6. The Mathematics of the model is as follows:

Table 1: Data for 5 mm RIM samples

Impact energy (J)	Response factor (No. units)
4.76	0.957
7.14	0.915
14.3	0.875
28.6	0.595
42.0	0.574
47.6	0.370
55.6	0.265

Table 2: Data for 2 mm RIM samples

Impact energy (J)	Response factor (No. units)
4.76	0.788
7.14	0.745
14.3	0.670
28.6	0.492
42.0	0.460
47.6	0.290
55.6	0.200

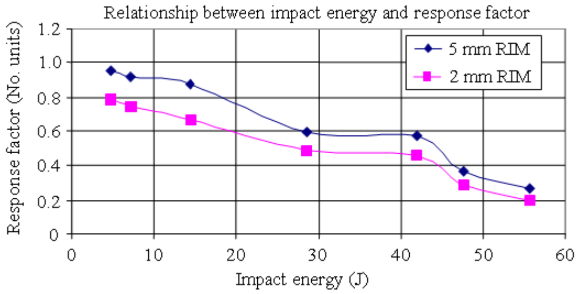

Fig. 3: Comparison between 5 and 2 mm RIM to impact energy

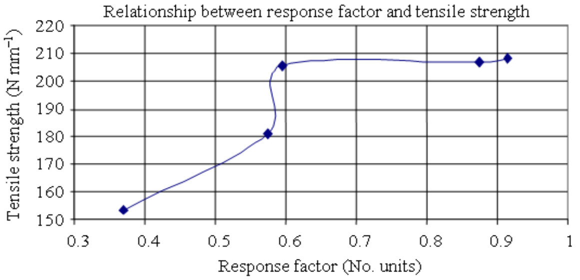

Fig. 4: Effect of impact energy on tensile strength

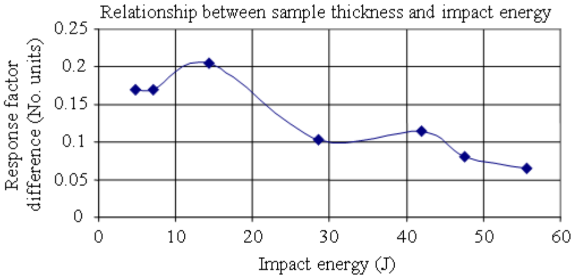

Fig. 5: Effect of impact energy on 5 and 2 mm RIM samples

Table 3: Data for 5 mm RIM sample

Impact energy	Response factor	Tensile strength
7.14	0.915	208.29
14.3	0.875	206.82
28.6	0.595	205.68
42.0	0.574	180.91
47.6	0.370	153.48

Table 4: Data for 5 and 2 mm RIM samples

Impact energy (J)	K_1 (5 mm)	K_1 (2 mm)	Diff
4.76	0.957	0.788	0.169
7.14	0.915	0.745	0.170
14.3	0.875	0.670	0.205
28.6	0.595	0.492	0.103
42.0	0.574	0.460	0.114
47.6	0.370	0.290	0.080
55.6	0.265	0.200	0.065

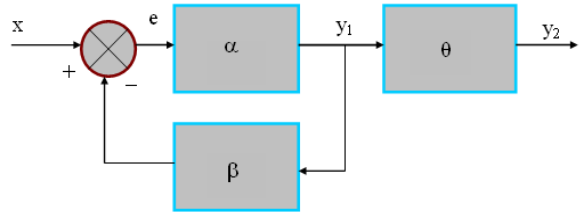

Fig. 6: System model for electronic tapping

The model in Fig. 6 represents a closed-loop feedback system. From the diagram we have:

$$x - \beta y_1 = e \tag{1}$$

$$y_1 = \alpha e \tag{2}$$

$$\left(\frac{x}{y_1}\right) = \frac{1}{K} = \left[\frac{1+\alpha\beta}{\alpha}\right] \tag{3}$$

With $\alpha = 1$ (No interface between the device and the structure) $\Rightarrow$ for a perfect sample:

$$k_1 = \left[\frac{1}{1+\beta}\right] \tag{4}$$

Substituting $y_2 = \theta y_1$ Results in the response factor for the manufactured, usually imperfect sample:

$$k_2 = \left[\frac{\theta}{1+\beta}\right] \tag{5}$$

With:

$$\beta = \left(\frac{t_m}{t_{ref}}\right) \tag{6}$$

$$\theta = \left(\frac{t_{avg}}{t_{ref}}\right) \tag{7}$$

Where:

t_{ref} = Reference response time
t_{avg} = Average response time
t_m = Measured response time
K = Relative response factor

For the dual transmission-reception operation and substituting (6) and (7) into (4) and (5), we obtain:

$$k_1 = \left[\frac{2t_{ref}}{t_{ref} + t_m}\right] \tag{8}$$

$$k_2 = \left[\frac{2t_{avg}}{t_m + t_{ref}}\right] \tag{9}$$

From the obtained expression (8) and (9), it is clear that a composite structure subjected to low frequency tapping has an overall response of two components:

- Defect introduced time delay due to damage
- Original structure response prior to damage

Hence, distinct cases needed for classification are realized:

- $t_m >> t_{ref}$: Both K_1 and K_2 are gradually reduced to small values and will approach 0 for critically or severely damaged structures, hence t_m will become t_{defect}. This reduces (8) and (9) to:

$$k_1 = \left[\frac{2t_{ref}}{t_{defect}}\right] \tag{10}$$

$$k_2 = \left[\frac{2t_{avg}}{t_{defect}}\right] \tag{11}$$

- $t_m \cong t_{ref}$: The structure is not affected by the impact, which happens at very low impact energies or when the tensile strength for the material is very high compared to the applied load. In this case K_1 will approach 1 as it should

Assume for a non-defective or acceptably damaged structure an energy level E_{th}. When seriously damaged, the defective area within the structure will hinder the flow of energy, hence, introducing a propagation delay to the applied tapping energy equivalent to the impact energy level that caused such damage denoted byE_I. Hence, an expression can be established correlating the introduced time delay to the required level of impact energy that can cause serious damage by obtaining the level of energy (threshold energy E_{th}) for both perfect and imperfect sample as a function of response times. Such energy need to be overcome for damage to occur.

MCIN model: Figure 7 shows a representation of the tested rectangular composite sample. To enable a two-dimensional classification, the sample is scanned in one-dimension multiple times starting from a certain location, then returning back to the location below the starting point ($y+\Delta y$). The used number of nodes will obviously affect accuracy and speed of convergence of the developed algorithm (Goebel *et al*., 2006a; 2006b; Hu *et al*., 2006; Eklund and Goebel, 2005; Verdegaya *et al*., 2008; Chinnam and Baruah, 2007; Jenab and Rashidi, 2009).

For a one dimensional, two-layer interpolation Gaussian network with the ability to predict an output y for a sample of inputs ($x_1, \ldots, x_n$), the output is related to the inputs via a weighted shaping function given by:

$$y(x_1,\ldots,x_n) = \sum_{i=1}^{s} w_i f(x_1,\ldots,x_n) \tag{12}$$

The function in (12) needs to operate under the conditions:

- The output values should be exactly equal to the values of the training set if training inputs are used
- The output values should be close to the outputs of the training set if other inputs are used
- f should reach a maximum or minimum peak value when the input values ($x_1,\ldots,x_n$) are close to the j^{th} input-output sample

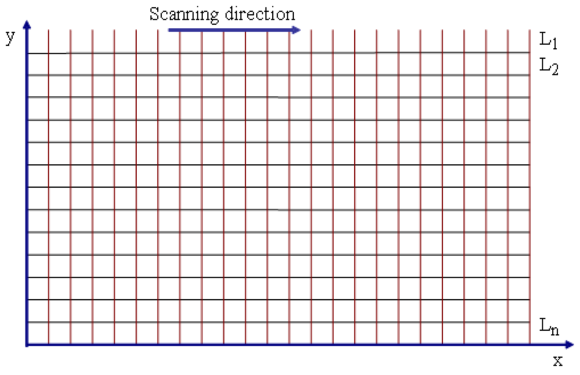

Fig. 7: Tested structure scanning algorithm

For ($x_1,\ldots,x_n$) fulfilling the following conditions:

- Considered as coordinates of vector x
- Associated with the j^{th} component of a Center vector R

Then:

$$f(x_i) = h\left(\left\|x_i - R_j\right\|\right) \tag{13}$$

This means that each f is handling the influence of the reference vector and the j^{th} component as well.

The Gaussian representation for (13) is given by:

$$f(x_i) = h\left(\left\|x_i - R_j\right\|\right) = e^{-\frac{1}{2\sigma}\left\|x_i - R_j\right\|^2} \tag{14}$$

From (12):

$$y(x_i) = \sum_{\substack{i=1\\ j=1}}^{\substack{m\\ n}} w_i e^{-\frac{1}{2\sigma}\left\|x_i - R_j\right\|^2} \tag{15}$$

where, σ controls generalization and function spread, with transition from local (low σ values) to global (high σ values) and w_i represents the associated set of weights.

For composite structures using electronic tapping, the weights for all tested points (nodes) are equal with value equal to 1. The center vector R which represents the averaged structure center value is given by:

$$R = \frac{t_{avg}}{t_{ref}} = \theta \tag{16}$$

The input vector values x are computed as:

$$x = \frac{t_{ref}}{t_m} = \frac{1}{\beta} \tag{17}$$

where, t_m (measured response time) will have the t_{ref} value for non damaged parts of the tested structure and will have the t_{defect} value for damaged parts. So for each value of scanned line in the x-direction per y-value, (15) becomes:

$$g(x) = \sum_{\substack{i=1\\ j=1}}^{\substack{m\\ n}} e^{-\frac{1}{2\sigma}\left\|\frac{1}{\beta_i} - \theta_j\right\|^2} \tag{18}$$

Equation 18 gives a maximum value when there is no or very little damage, where $t_{ref} \approx t_m \approx t_{avg}$ which gives a maximum value for the classification function.

Table 5: Classification data

E_i	g(x),σ = 0.5	g(x),σ = 1	g(x),σ = 2	g(x),σ = 4	Decision
5 mm RIM					
4.76	0.9958	0.9980	0.9989	0.9999	*
7.14	0.9835	0.9917	0.9958	0.9979	*
14.3	0.9637	0.9817	0.9908	0.9954	*
28.6	0.6479	0.8049	0.9011	0.9472	#
42.0	0.6157	0.7847	0.8858	0.9412	#
47.6	0.3042	0.5516	0.7427	0.8618	#
55.6	0.1773	0.4211	0.6489	0.8055	#
2 mm RIM					
4.76	0.9001	0.9465	0.9729	0.9863	*
7.14	0.9011	0.9231	0.9608	0.9802	*
14.3	0.7558	0.8694	0.9324	0.9656	#
28.6	0.4677	0.6839	0.8269	0.9094	#
42.0	0.4360	0.6603	0.8126	0.9015	#
47.6	0.2020	0.4493	0.6703	0.8187	#
55.6	0.1165	0.3413	0.5842	0.7643	#

*: Accept #: Reject

For a damaged structure, $t_{ref} < t_m$ and $t_{ref} < t_{avg}$, hence, $\frac{1}{\beta} < \theta$, which gives (18) minimum values that might reach zero for sever damages. The derived function in (18) is thickness independent as it compensate for it by using time response ratio, which implicitly include thickness effect on judging level of damage.

Acceptability for damage is decided in conjunction with the value of σ where the higher its value is set the more damage or defects in the structure are accepted. This allows for component functionality and its critical role to be considered in the calculation, as some structures which are considered unusable in certain applications can be used in others. Table 5 shows classification results for 5 and 2 mm RIM samples with tolerance set at 10%.

Two important points characterizing the obtained results:

- The ability to observe the change from undamaged to damaged. For 2 mm samples, 14.3 J marks the start of damage as the classification function starts to noticeably drop in value with 28.6 J indicates the start of sever damage. For 5 mm samples it is found to be 28.6 J for the start of damage with 42 J pointing towards the start of a sever damage. This difference in Impact energy levels is consistent with both the difference in thickness and the mathematical model developed earlier
- The ability to correlate thickness, Tensile Strength, composite type to impact energy through Electronic Tapping should enable the use of intelligent systems that make use of such information to carry out data prediction, association and classification through the life span of a component. This finding is very important with the implication of faster and less laborious way of finding out structural integrity without the need to carry out destructive testing. It also means that structural testing can be brought out of laboratories and factories and be used in everyday testing work

CONCLUSION

A mathematical model of RIM composite response to impact energy is developed and presented. The effectiveness of the Electronic Tapping device in damage detection was established. A relationship between the mechanical properties and the response time was analyzed and linked through the Response Factor. Points of transition from undamaged to damaged and severely damaged components are observed and proved to be a function of both Impact Energy and component thickness. Classification function based on Gaussian interpolation is developed, applied and proved to be valid in the classification algorithm used in the work.

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