VALIDATION OF A PROGRESSIVE FAILURE PREDICTION TOOL FOR A DYNAMICALLY LOADED THREE DIMENSIONAL COMPOSITE SHIP STRUCTURE

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Abstract

The application of complex fiber reinforced composite structures is increasing. This calls for a better understanding of the behavior of these structures, including the propagation of damage. In this research a secondary bondline failure model was developed as part of a failure prediction tool. Validation against laboratory experiments of hat stiffened panels in shock loading conditions showed good results. Also the application of the model in a large scale ship structure demonstrator gave reasonable agreement with previous experiments.

1 Introduction

The utilization of complex fiber reinforced composite structures in both civil and naval ship applications has grown in response to the need for improved performance. The required lighter weight and complexity of these structures increases the need for optimization of the structural elements, emphasizing the need to achieve acceptable margins for the operational loads. The understanding and limitation of the propagation of damage incurred from slamming loading and/or damage development and propagation under blast or indirect shock pressure loading is of primary importance in developing robust optimal structural designs.

To increase the understanding of these composite structures TNO and NSWCCD jointly developed, within the Dycoss project, a failure prediction tool (FPT) for solid laminate delamination, fillet material cracking, bondline failure between structural component (e.g. stiffener/panel debonding) and sandwich core failure. The first three failure models are described in more detail in [1], while the sandwich core model is given in [2]. The models were implemented in the explicit finite element code LS-DYNA as user subroutines and validated against laboratory scaled tests and some full scale tests on composite hull structures. The first three models are now also available within the official LS-DYNA release.

In this paper the focus will be on the bondline failure model, which is critically important for hat stiffened panels. This failure mechanism can lead to large structural stiffness and strength degradation. The three dimensional progressive bondline failure model, which is a part of the FPT, will be briefly presented. Validation of the model through shock table tests of single straight hat stiffened panels is shown. This validation was used to further develop the methodology of the numerical bondline failure model usage. Blind validations against more complex cross stiffened shock loaded panels are given, showing a good comparison. A final demonstration of the capabilities is given in a demonstrator analysis of a composite ship hull.

2 Bondline failure model

The secondary bondline failure model, implemented in LS-DYNA as a tiebreak contact entity (*CONTACT_AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE_TIEBREAK) was used in the project. It describes a mixed mode (G_I and G_{II}) fracture on known interfaces. (Figure 1) shows the 3D representation of the model. Up to failure initiation the behaviour of the tiebreak contact interface is elastic, while a linear post failure progressive unloading is implemented based on damage mechanics. The mixed mode identity of the model is governed by a quadratic description of the failure locus, given by Equation 1.

$$\begin{aligned} &\textit{initiation}\ (D=0) \rightarrow \left(\frac{\max(f_n,0}{f_{n,t}}\right)^2 + \left(\frac{f_s}{f_{s,t}\left(1-\sin(\theta)\min(0, f_n\right)}\right)^2 < 1 \\ &\textit{evolution}\ (0<D<1) \rightarrow \left(\frac{\Delta u_n}{D\Delta u_{n,ult} + \Delta u_{n,ini}}\right)^2 + \left(\frac{\Delta u_s}{D\Delta u_{s,ult} + \Delta u_{s,ini}}\right)^2 = 1 \end{aligned} \tag{1}$$

Where f_i is the interface traction in normal (n) or shear (s) directions, while Δu is the displacement. The subscripts ini and ult represent the interface displacement at failure initiation and ultimate failure respectively. The friction angle is given by θ.

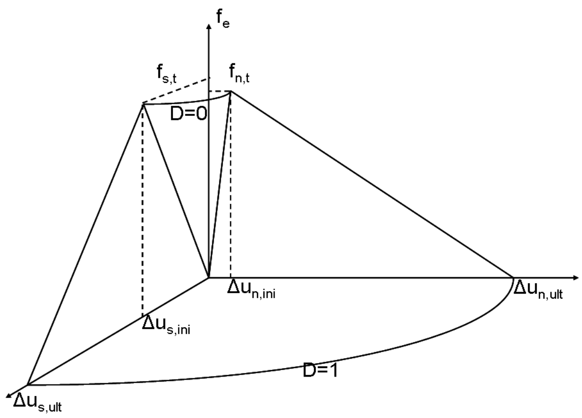


Figure 1 3D representation of the bondline failure model

3 Shock table experiments on hat stiffened composite panels

Several tests have been done in the TNO laboratory for validation of the developed material model. All specimens were tested on the shock tables of TNO, which subject the specimen to a predefined shock loading. It is good practice within the Dycoss project to first tune/validate the models by means of relatively simple experiments, in this case single hat stiffened panels as shown in Figure 2. To trigger bondline failure a mass was attached to the stiffener. Figure 3 shows some stills of the high speed video recordings during the tests. Secondary bondline failure develops, initiating below the attached mass and progressing to the ends of the specimen. The panels and the test table were instrumented using strain gauges and accelerometers for material model validation.

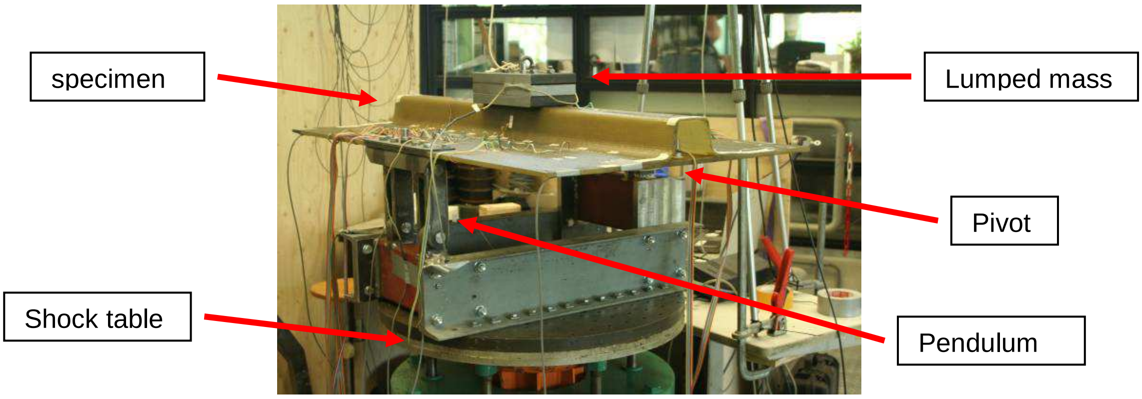


Figure 2 Single hat stiffened panel on the TNO shock table

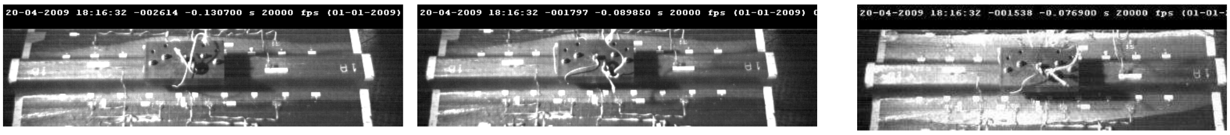


Figure 3 Secondary bondline failure development during test, increasing from left to right

After the experiments for model tuning a blind validation is normally carried out within Dycoss projects for more complex specimens. Within this project, these complex specimens consisted of cross stiffened panels (Figure 4). Figure 5 show the resulting bondline failure of one of the tested panels after shock loading. The interaction between the stiffeners was clearly seen in the experiments, leading to more complex debonding patterns.

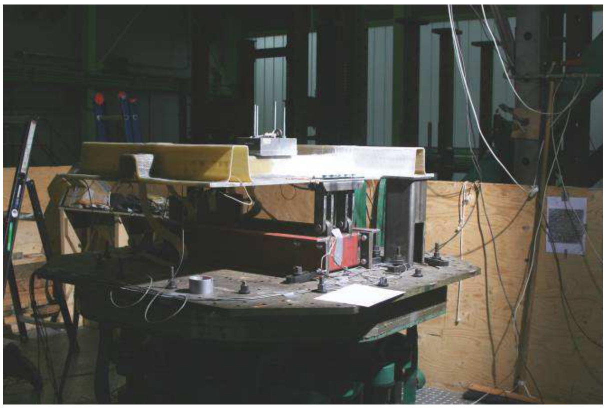


Figure 4 Cross stiffened specimen on shock table

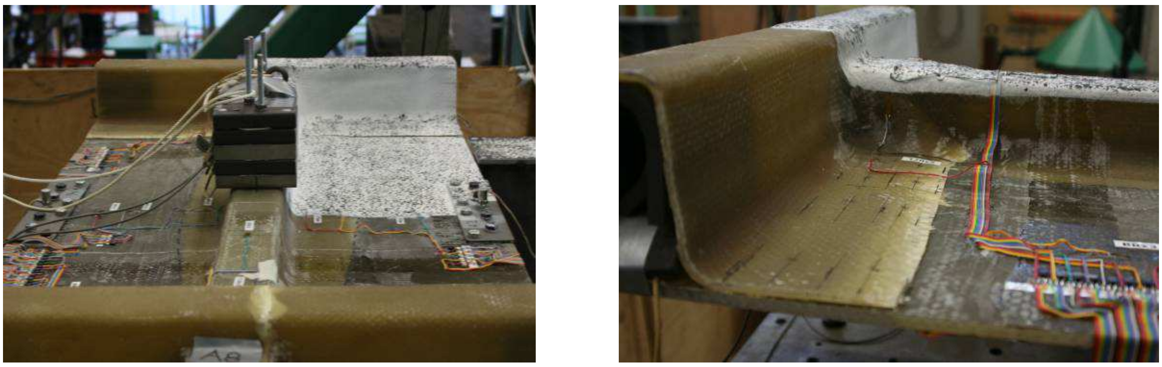


Figure 5 Bondline failure cross stiffened panel (left: debonded longitudinal stifferer, right: debonding of one of the transverse stiffeners and interaction with longitudinal)

4 Validation of bondline failure model against laboratory experiments

4.1 Tuning of model against single stiffener panels

The 3D bondline failure model is applied to simulate the single stiffener shock table experiments. Both the panel and upper part (pivot and pendulum) of the test frame were modeled. Shock table loading was applied on the bottom of the pivot and pendulum. It was the first time the 3D bondline failure model was applied in combination with shell element approximations of the laminates. Results were very good, although it was seen that the shell element representation showed a slightly lagging debonding compared to solid element modeling of the tests. Since the debonding progression is hard to determine exactly from the high speed video in the tests, the best representation is debatable. Figure 6 shows the debonding pattern development in the shell element analysis. The results are given at the times corresponding to the high speed video stills of Figure 3. Note that only half of the panel is shown, with the lumped mass located at the origin of the figure. Reasonable test/analysis agreement is seen in the debonding development. The debonding at the stiffener tabbing edges is due to numerical effects when using the shell element representation. Figure 7A) shows the measured and calculated strain gauge response of a gauge located in the transverse direction on the overlap of the stiffener and the panel below the mass, so in the debonding area. A good comparison is seen. Also the mass motions are well predicted as can be seen in Figure 7B) which shows the lumped mass velocity during the shock loading. A small difference in the response frequency is seen, which could be due to difference in mass of the tested specimen and the FE model.

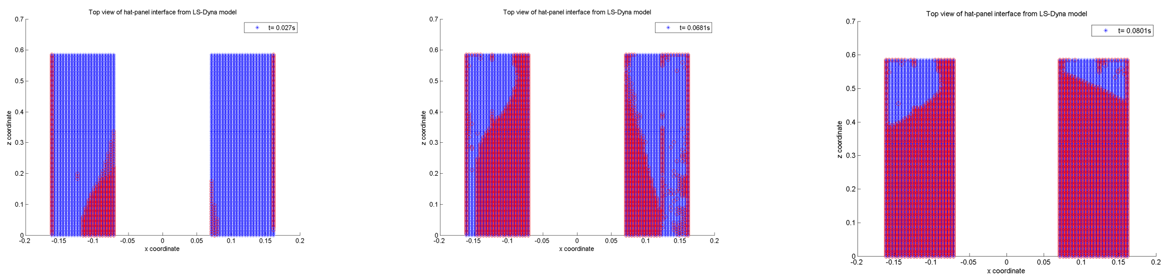
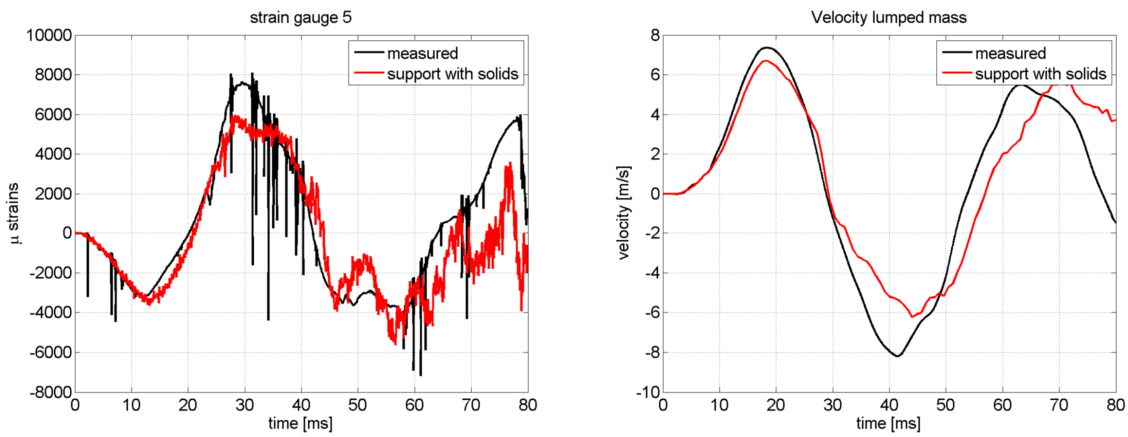


Figure 6 Debonding patterns (red is fully debonded) at times corresponding to the high speed video stills of Figure 3



A) Strain gauge transverse direction on stiffener overlap below mass

B) Velocity lumped mass connected to specimen

Figure 7 Comparison of measured and calculated specimen responses. The calculated results are obtained by modeling the panel at the specimen supports with solid elements

During this validation it was found that the results can be largely influenced by some modeling details. For example it was seen that the time step used in the explicit analyses should be below the critical value given by LS-DYNA for accurate results. Also the mesh size and initial stiffness of the interface are closely linked. A final important aspect for correct modeling is the connection between the panel and the pivot and pendulum. Due to the shell modeling of the specimen, force and specifically moment transfer from frame to specimen was not straightforward. A solution was found in solid modeling of the part of the specimen connected to the frame.

4.2 Blind validation against cross stiffened panel experiments

With the lessons learned in the single stiffener panel validation, a blind validation was done for the more complex cross stiffener panels. Due to symmetry only half of the specimen and setup were modeled (Figure 8).

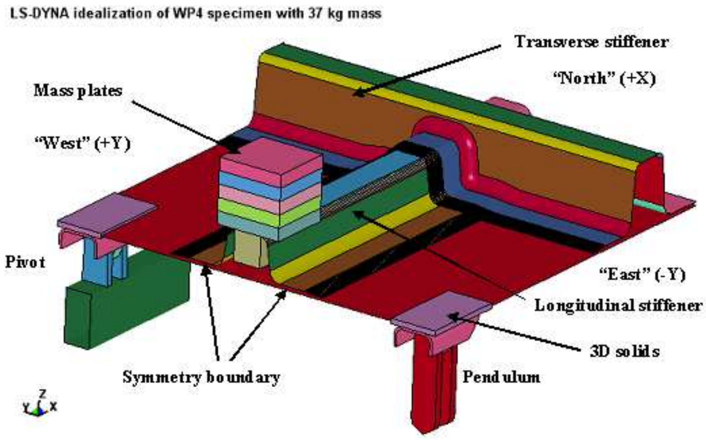


Figure 8 FE model of half of the cross stiffened panel

The comparison of the kinematic responses of the panel was rather good, as can be seen in Figure 9 showing the velocity of the lumped mass. Again the small elongated fundamental period is seen in the analysis. Also most strain gauge compare reasonably well with the measured values (Figure 10). Only very low measured strain amplitude signals are normally overestimated by the LS-DYNA analysis as can be seen from subfigure C of Figure 10.

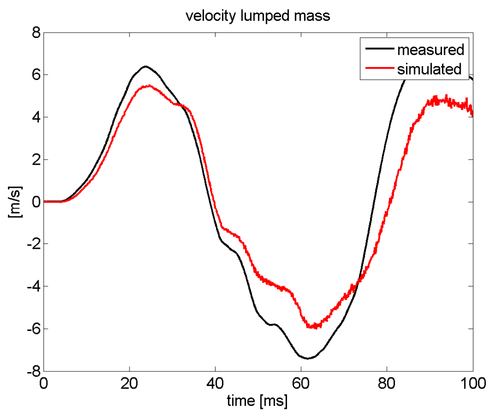
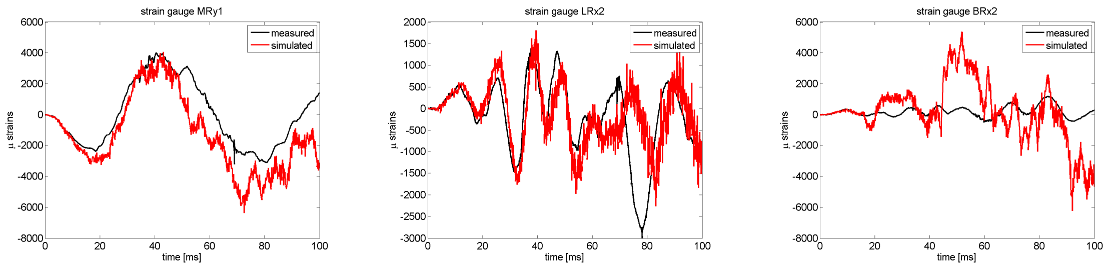


Figure 9 Velocity of the lumped mass during the shock test



A) Transverse strain on base panel at symmetry line

B) Longitudinal strain on top of longitudinal stiffener

C) Longitudinal strain in on base panel close to support

Figure 10 Strain gauge comparisons for cross stiffened panel

Figure 11 gives the final debonding at the end the analysis. The analysis results are presented separately for the longitudinal and transverse stiffener. Complete debonding is again indicated by the red color. A full debonding of the transverse stiffeners was found in both the analysis and the experiment. Extended debonding was found in the analysis starting below the mass and extending towards the transverse stiffeners. A similar pattern was observed in the tests (Figure 5).

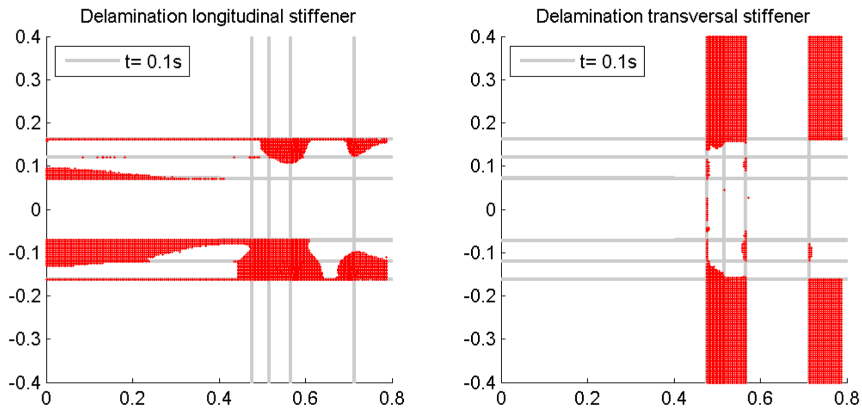


Figure 11 Debonding pattern at the end of the analysis (left: longitudinal stiffener, right: transverse stiffener)

5. Large scale demonstrator application

While a validation against laboratory scale test specimens is extremely useful, the real validity of the developed failure models lies in the successful application in large scale structures, such as ships. Therefore the described model was applied to a large scale demonstrator application. Several years ago a composite surface ship hull section composed of hat-stiffened panels was tested in under water explosion conditions. Although exact results of these tests could not be provided, sufficient data and photographic evidence was present to simulate a comparable scenario with the secondary bondline failure model. One of the main complications of this specific test was the loading, which included the fluid structure interaction of a lightweight flexible target floating on the air/water interface. Much effort was put into the reasonably accurate modeling of this interaction, without compromising on the analysis time. A solution was found in the application of the Simplified Interaction Tool (SIT) [3]. This tool is a user supplied pressure loading module linked with LS-DYNA, which takes into account pressure loading due to the explosion phenomena, bulk cavitation, surface reflection and fluid structure interaction. To ensure a reasonably accurate SIT loading calculation, several comparisons with analyses obtained with an Eulerian fluid/Lagrangian structure coupled code were made.

To limit the analysis time and since this was only a demonstrator for large scale application, a symmetry plane was assumed in the analysis. Also the area in which the bondline failure model was applied was limited to the area where this type of damage was seen in the tests (area indicated by the red ellipse in Figure 12). Figure 13 shows the mesh refinement. Element sizes are approximately 5x5 mm.

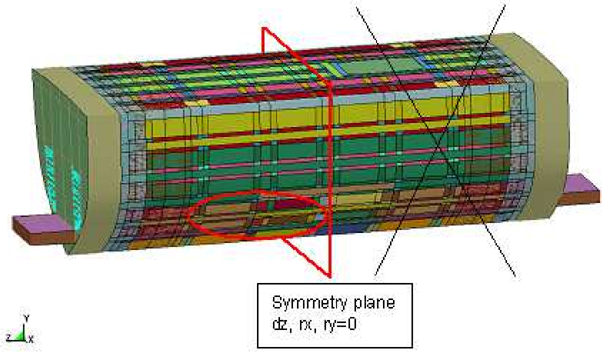


Figure 12 FE model of the CHS with the refined area indicated in the red ellipse. The crossed out section was not included due to symmetry assumptions.

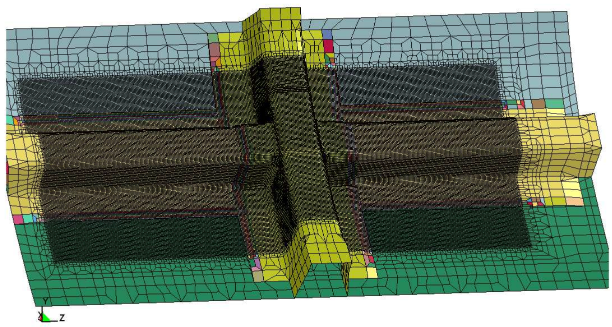


Figure 13 Mesh refinement area

Since no actual data was available, only a global comparison of the observed failure was done. Figure 14 shows the bondline failure at the end of the analysis (red completely failed) and a picture of the post test damage along the same stiffener. Debonding patterns are similar, with an ellipse shaped debonding along the longitudinal stiffener at the inner side of the hat. The numerical results also show some unexplainable stiffener tabbing edge failure. This could have numerical causes, but this is not verified yet.

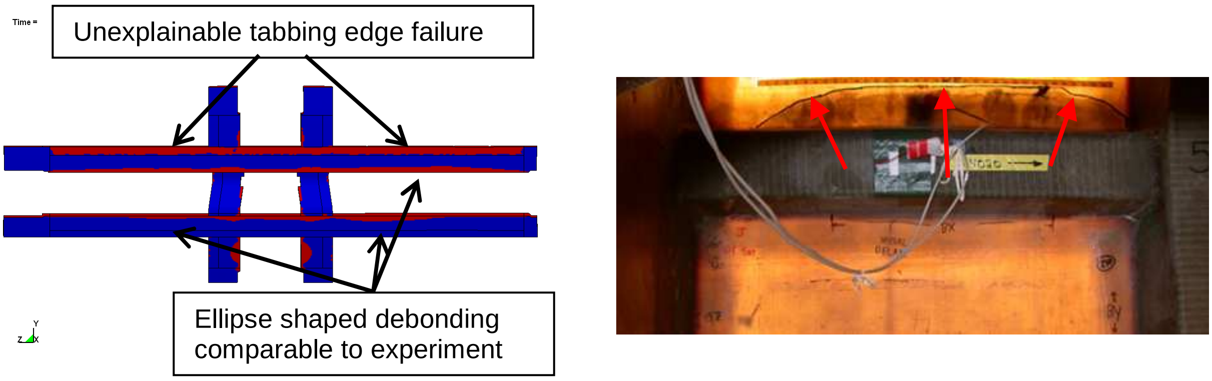


Figure 14 Global comparison of observed debonding at similar loading conditions

6. Conclusions

The secondary bondline failure model, developed within the Dycoss model and now implemented in LS-DYNA in both 2D and 3D, is capable of accurately predicting the damage response of fiber reinforced composite hat stiffened panels. In combination with shell elements, application of the model in debonding analyses of judiciously limited portions of large structures seems feasible.

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