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Reducing the Notch Sensitivity of Quasi-Isotropic Layups using Thin-Ply Hybrid Laminates

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ABSTRACT

The concept of stress concentration suppression using thin-ply pseudo-ductile hybrid composites is presented in this paper. In previous works, it has been shown that it is possible to achieve high amounts of pseudo-ductility in Uni-Directional (UD) and multi-directional laminates. In this work, the requirements for thin-ply hybrid sub-laminates to suppress/reduce notch sensitivity in quasi-isotropic laminates with an open hole is studied. A User Material subroutine (UMAT) has been developed in ABAQUS which can replicate the typical response of pseudo-ductile thin-ply hybrids. This UMAT was then used to study several idealised responses and find the important parameters controlling the fibre failure in notched specimens. The stress concentration factor in the 0° layer has been selected as a measure of notch sensitivity. The ratio of pseudo-ductile strain to initiation strain has also been found to be a useful parameter in comparing different fibre direction tensile responses. The stress concentration factors of the 0° layer found from two different tensile response shapes of UD sub-laminates were found to be very similar when they were plotted versus the ratio of pseudo-ductile strain over initiation strain. These results show that the stress concentration factor varies between 3 for linear elastic material response to 1 for sub-laminates with pseudo-ductile strain to initiation strain ratio of 3. This suggests that optimal structural response can be achieved with thin ply hybrids if the failure strain of the low strain material to high strain material is about 25%.

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1. INTRODUCTION

Lack of ductility in composite materials is one of their main drawbacks that results in over-designed structures and unexploited weight saving potential. Among different approaches to address this issue, it has been shown that a pseudo-ductile failure development can be achieved with thin-ply hybrid composites if they are well designed [1]. Different types of hybrid composites have been developed in the HiPerDuCT programme grant. Continuous prepreg layers [2–4], discontinuous fibres [5] and discontinuous layers [6] are some of the configurations in which pseudo-ductile tensile behaviour has been achieved. However, in all of these cases, the mechanical properties of the unidirectional specimen are good only in one direction. These UD specimens are not capable of dealing with multi-directional loading cases and more complex geometries such as open holes. In fact, this is why unidirectional layups are not widely used in industrial applications, especially in primary structures and where there are complex geometries.

Previous analytical studies in the HiPerDuCT programme [7] showed the possibility of getting pseudo-ductility in multi-directional hybrid laminates. In this study, the focus is on the structural aspects. Among different structural elements, tensile specimens with open holes were selected for this study. Strength of notched specimens depends on various parameters including UD layer strength, sub-laminate ply thickness and layup sequence. Some of these parameters have been extensively studied [7]. However, the effect of nonlinear UD sub-laminate response has not been studied before to the best knowledge of the authors.

Many different types of nonlinear tensile UD response can be assumed, so finding an effective way of processing and presenting the results is very important. Finding a baseline for such a study is also quite crucial and not easy. The final goal however, should be to simplify the results since the parameters are not proportional in nonlinear problems.

To simplify the analysis, a 2D plane stress FE approach is selected in which the interlaminar damage is ignored. Free edge delamination and in-plane splitting are not taken into account since the focus is to model thin-ply hybrid laminates and it has been proved that free edge effects are suppressed using these materials [8]. This means that the obtained stress concentration around the hole is overestimated and therefore, the required pseudo-ductility for a good structural response found in this report is conservative. The Stress Concentration Factor (SCF) has been found to be a useful measure of the notch sensitivity in linear elastic materials and it will be used here as well.

2. USER DEFINED MATERIAL MODEL (UMAT)

The damage process of UD hybrid sub-laminates can be divided into four different types: high strain material premature failure, catastrophic delamination, fragmentation of low strain material and finally, fragmentation of low strain material followed by dispersed delamination. If premature high strain material failure and catastrophic delamination are avoided by selecting the right configuration, the stress-strain curve of the UD laminate includes a plateau region and a final rise.

Typical pseudo-ductile UD hybrid stress-strain curves are shown in Figure 1. If the damage process comprises delamination, the idealised final stress rise consists of two straight lines and in the other case, it is only one straight line. Therefore, the whole stress-strain curve of the UD laminate can be approximated by 3 or 4 straight lines. The properties in other directions vary much less during fragmentation and dispersed delamination so they will be taken as constants while the fibre direction modulus will be considered as changing. Both of the responses shown in Figure 1 can be approximated by three straight lines. Although 3 straight lines are not ideal for the response with delamination (Fig 1b) which originally has four straight lines, it is possible to approximate it with enough accuracy for the current study.

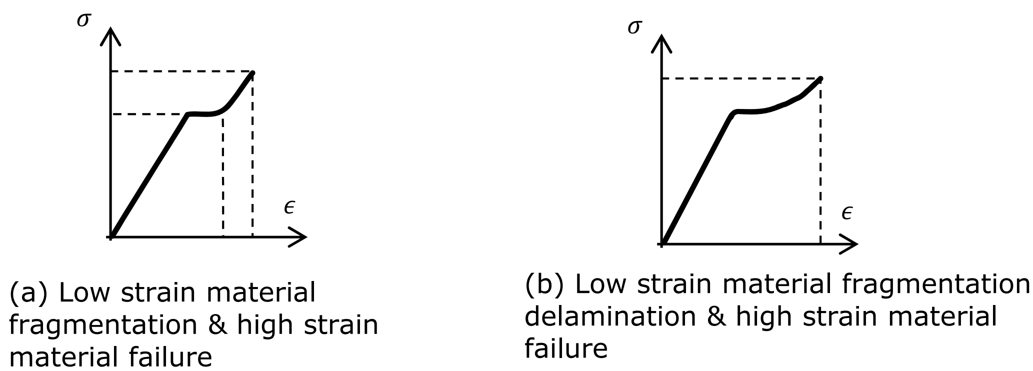

Figure 1. Analytical stress-strain curves of UD hybrid sub-laminates with pseudo-ductility and gradual failure

3. FINITE ELEMENT MODELLING

The tensile response of the specimens with an open hole are modelled with 2D plane stress analysis. The stress concentration factor is equal to 3 in a 2D analysis of a wide specimen with isotropic or quasi-isotropic material. Quadratic plane stress elements of type CPS8 along with Abaqus Composite Layup toolbox have been used to model the $[45/90/-45/0]_s$ quasi-isotropic laminates and the behaviour of each ply was defined using the developed UMAT Subroutine.

A tensile model with Length (L) to Width (W) ratio of L/W=5 is considered. To reduce the effect of width on the stress distribution around the hole, a relatively large ratio of Width to hole Diameter (D) W/D=20 was selected, which has a finite width correction factor of only 1.001. Assuming that the diameter is equal to D=3 mm, width and length of the tensile specimen are W=60 mm and L = 300 mm. The applied mesh and element size around the hole are shown in Figure 2. The size of the smallest elements around the hole is about 0.31 mm. Element size was gradually increased in areas with lower stress gradient for computational savings.

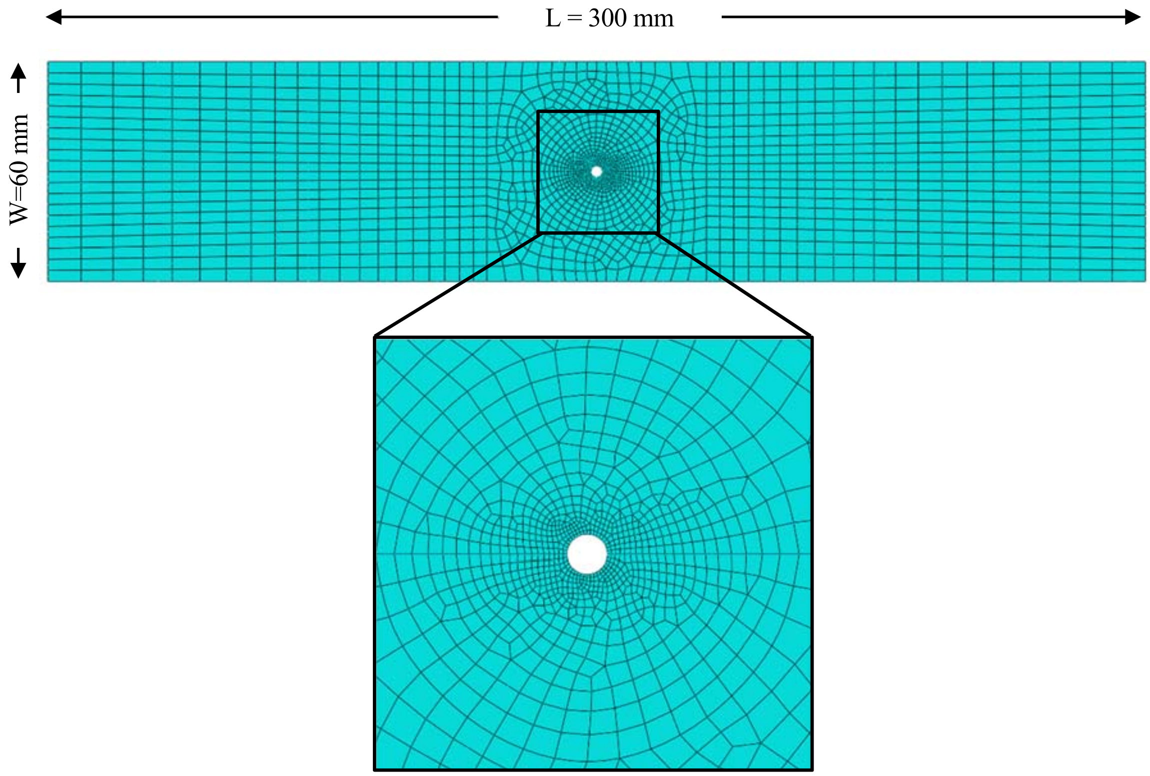

Figure 2. Meshed tensile specimen with open hole, W/D=20 and L/W=5

4. RESULTS AND DISCUSSIONS

To simplify the analysis, an ideal elastic perfectly-plastic response is assumed and the effect of different parameters on the stress concentration factor and strength of the notched specimen is studied. For the elastic-perfectly plastic response, the first two segments of the 3 straight-line UMAT are used and the last segment is deleted from the response, providing conservative results.

Elastic-perfectly plastic response is an idealisation of the fragmentation followed by dispersed delamination in the thin-ply hybrid laminates. By fixing the initial elastic part of the response and assuming different failure strains, it is possible to study the effect of the amount of pseudo-ductile strain. To build upon an available promising case, a recently tested hybrid experimental stress-strain curve has been chosen as the basis and other arbitrary elastic-perfectly-plastic material responses with the same initial elastic modulus and yield stress were assumed. Figure 3 indicates the idealised hybrid tensile response as well as some of the other elastic perfectly-plastic responses. To keep the image clear, only three of the assumed materials are plotted. The damage initiation strain of all of the responses is assumed to be 0.4% and the yield stress is equal to 1009 MPa, with a modulus of 357.5 GPa according to the experiments. The only difference between them is the final failure strain which varies between 0.4% for the linear elastic one to 5.0% for the highest pseudo-ductile strain case.

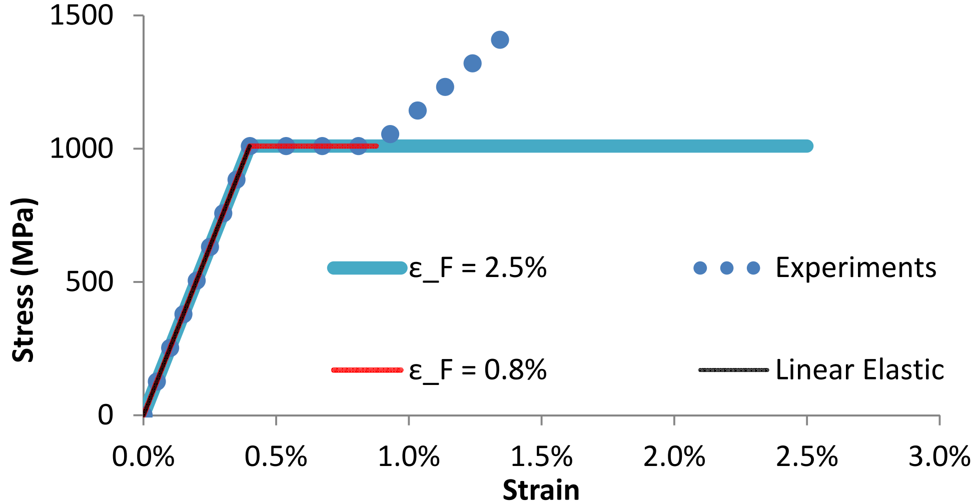

Figure 3. Three elastic-perfectly plastic UD hybrid sublaminate stress-strain curves and the idealised experimental results

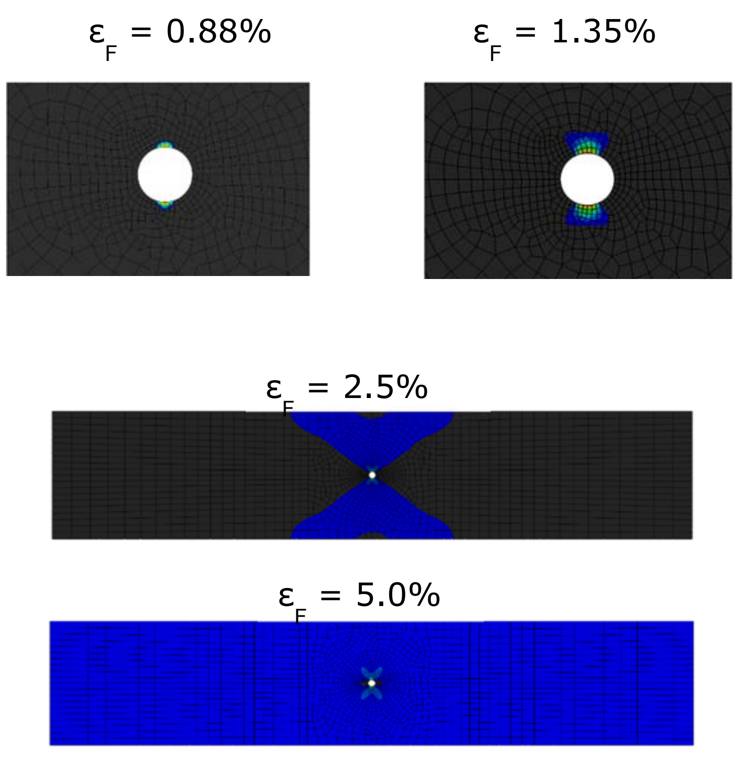

Figure 4. Damaged area in the 0° layer around the hole with different UD sublaminate tensile responses all with initiation strain of 0.4% and different failure strains of 0.8%, 1.35%, 2.5% and 5.0%

If the tensile fibre-direction strain is more than 0.4%, the sub-laminate has started its nonlinear stress-strain response, so this can be used as a damage initiation criterion. In Figure 4, the coloured areas are where the fibre direction strain is larger than 0.4% at the final failure load of the specimen, defined as when the most highly loaded point reaches the ultimate strain. Therefore, these coloured areas correspond to where damage has initiated just before final failure for different elastic perfectly-plastic UD responses. Materials with higher failure strains and pseudo-ductility have larger damaged areas before final failure, as expected.

The stress concentration factor in a notched specimen is defined here as the maximum value of stress divided by the far field stress. The overall laminate stress is not a good way of measuring the stress concentration factor if some of the layers have nonlinear tensile response. On the other hand, the 0° layer is the main component of the layup, carrying most of the applied load, contributing pseudo-ductility and determining the final failure of the specimen. Therefore, the applied stress concentration factors in this paper are all based on the stress values in the 0° layer.

Figure 5 indicates the fibre direction stress divided by the far field fibre direction stress for two cases of UD material with linear elastic and elastic perfectly-plastic responses.

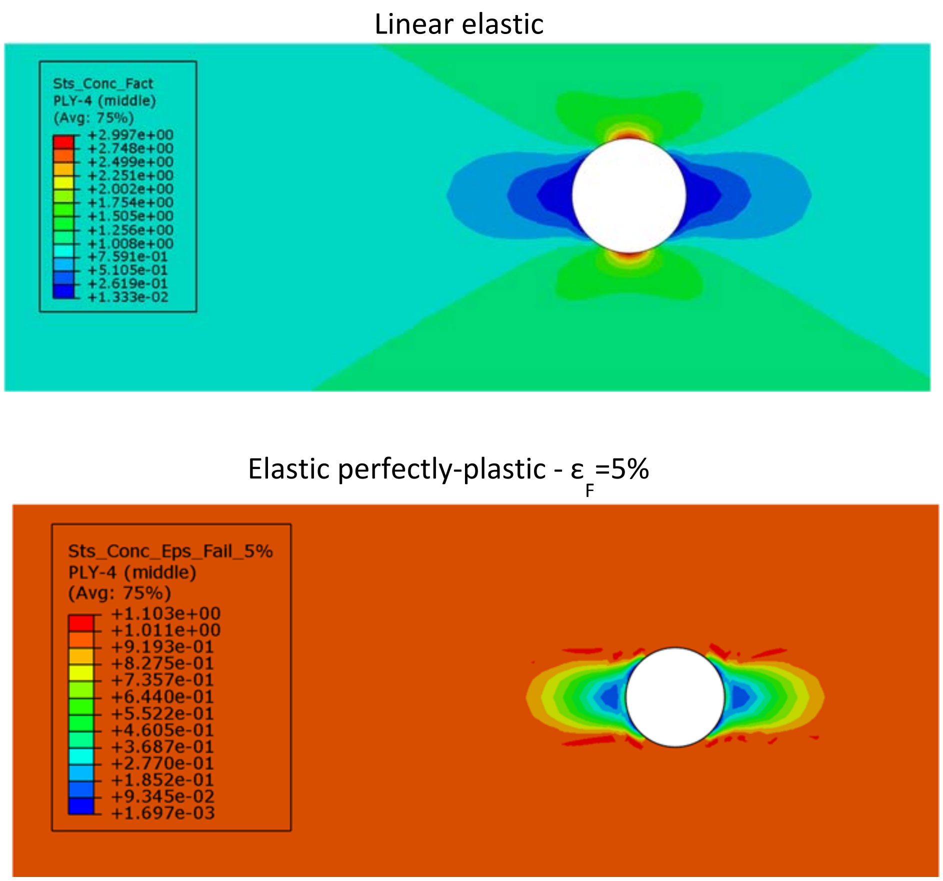

Figure 5. Fibre direction stress divided by far field stress in the 0° layer near the hole for two cases of linear elastic material and elastic perfectly-plastic material with failure strain of 5%.

The results of the notched specimen analyses with different UD material responses are given in Table 1. The first column is for the experimental UD hybrid response and the second column is for a linear elastic response with the same initial stiffness and initiation strain. There are four other cases with UD sub-laminates with elastic perfectly-plastic responses with different final failure strains from 0.88% to 5.0%.

The UD sub-laminate properties are the input parameters of the FE model, separated in Table 1 from the final FE results of the quasi-isotropic laminates with open holes. The analysis is stopped when the UD failure strain is reached at the hole and the far field failure strain is quoted in Table 1. The value of the notched Quasi-Isotropic (QI) failure stress is found by dividing the total applied force by the cross-sectional area of the specimen where the boundary conditions are applied.

To compare the strength of different notched specimens, it is helpful to normalise them. The strength of the unnotched quasi-isotropic laminate with linear elastic sub-laminates is used for normalising the strength of the notched QI specimens. This value is defined here as the sub-laminate fibre-direction failure strain multiplied by the QI laminate modulus. For the current case, the strength of the quasi-isotropic laminate is equal to 0.4% × 90.7 GPa = 363.0 MPa. The normalised strength values of the quasi-isotropic laminates with open holes are given in Table 1. The effective concentration factor is the inverse of the normalised strength and it should be equal to 3 for the linear elastic case. The value of 2.9 shown in Table 1 would be closer to 3 if a finer mesh was applied.

The stress concentration factor in the 0° layer is also given in Table 1. This factor is defined as the maximum stress in the 0° layer divided by the far field stress value in the 0° layer. For cases with lower pseudo-ductility, this value is equal to the strength reduction factor but for highly pseudo-ductile sub-laminates, the stress concentration value in the 0° layer stays equal to 1. In other words, 1 is the minimum value for this factor.

Figure 6 shows the variation of stress concentration factor in the 0° layer in terms of the normalised pseudo-ductility (ratio of pseudo-ductile strain to initiation strain). The first point on the y axis with zero pseudo-ductile strain is for the linear elastic UD response and as shown in Figure 5, the stress concentration in this case is equal to 3. The reason of getting a stress concentration slightly lower than 3 in Figure 6 is because the calculation for this graph is carried out based on stress values at Gaussian integration points which are slightly off the hole edge. Other cases with nonlinear tensile response show significantly lower stress concentration factors. For the case with a normalised pseudo-ductile strain of 3, the stress concentration factor is only 1.1 which means that the stress concentration is almost completely suppressed in this case. Please note that more cases have been included in Figure 6 compared with Table 1.

Table 1. Results from notched specimen with similar geometries and layups but different elastic perfectly-plastic UD response

	Material response	Exper.[I]	Linear-Elastic	Elastic perfectly-plastic			
Input parameters	UD Failure strain	1.35%	0.40%	0.88%	1.35%	2.50%	5.00%
	UD Strength (MPa)	1420	1009	1009	1009	1009	1009
	UD Pseudo-ductile strain	0.79%	0.00%	0.48%	0.95%	2.10%	4.60%
	UD Pseudo-ductile strain / UD Initiation strain	2.0	0.0	1.2	2.4	5.3	11.5
Output parameters	Notched QI far field failure strain [II]	0.36%	0.14%	0.20%	0.30%	0.45%	0.70%
	Notched QI far field failure stress (MPa) [III]	326	127	181	272	407	446
	Notched QI Normalised strength [IV]	90%	35%	50%	75%	112%	123%
	Stress concentration factor in the 0° layer [V]	1.6	2.9	2.0	1.3	1.0	1.0

[I] An experiment-based 3-part tensile stress-strain curve with (i) linear elastic, (ii) perfectly plastic and (iii) strain hardening behaviour. See Figure 3.
[II] Far field strain value when the points at the hole reach the ultimate fibre direction strain.
[III] Far field stress value when the points at the hole reach the ultimate fibre direction strain.
[IV] Far field stress value divided by the strength of the unnotched QI laminate with linear elastic sub-laminates.
[V] Maximum stress in the 0° layer divided by far field stress in the 0° layer.

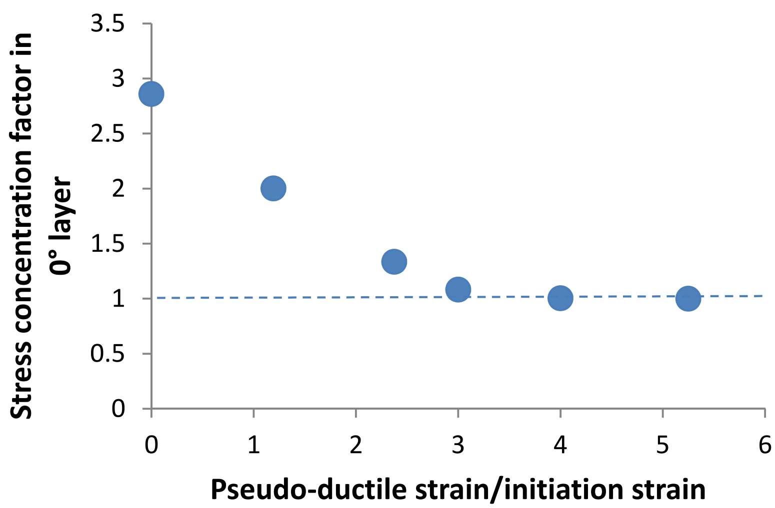

Figure 6. Stress concentration factor in the 0° layer versus the ratio of pseudo-ductile strain to initiation strain (Compared to Table 1, more UD hybrid sublaminate responses are included)

5. CONCLUSION

In this paper, the possibility of using thin-ply hybrids for reducing the notch sensitivity of quasi-isotropic laminates with open holes has been studied. Since the 0°

layers carry most of the applied load in a [-45/90/45/0]s laminate, the stress concentration factor in the 0° layers was selected as a measure of notch sensitivity. It has been found that the stress concentration factor in the 0° layer varies from 3 for a linear elastic material to 1 for a sub-laminate with pseudo-ductile strain at least three times its initiation strain. The ratio of pseudo-ductile strain to initiation strain has been found to be a useful measure in comparing different tensile responses. This suggests that to obtain an optimal structural response, the ratio of failure strain of the low to high strain material in a thin-ply hybrid should be around 25%.

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