



Effects of lamination and spacing on finite thickness plate perforation

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Abstract

In determining ballistic limits and residual projectile characteristics for very thick targets (situations where the ratio of target thickness T to projectile diameter D exceeds 10), resort must frequently be made to constructing the target from a number of layers whose thickness is less than that of the monoblock target. This holds true for determining penetration depths in semi-infinite plates as well. This paper presents results of numerical simulations comparing projectile residual characteristics, primarily residual mass, for monoblock and equivalent thickness layered targets for a number of situations involving $T/D < 1$ to $T/D > 10$. It is found that for thick plates, results obtained from layered target perforation compare favorably with those from monoblock targets provided that the layering is not excessive and care is taken to insure that the individual layers have the same material properties as the monoblock target. For thin targets, the correlation ranges from poor to non-existent.

Introduction

Impact and impulsive loading onto layered media - targets consisting of different materials - is a problem of long standing. It occurs naturally when dealing with impact effects into geological media, where different strata have different material properties. It can occur in the design of protective structures where materials of different density, strength and cross-sectional area are employed to reduce the intensity of the impact stress. This aspect of the impact problem is well understood and is covered in modern textbooks and reference books dealing with transient phenomena.

Another aspect of layering involves the impact of projectiles onto targets consisting of multiple layers of plates of the same density. In impact testing, this often occurs when very thick targets need to be constructed yet the target material in question is not manufactured in the required thickness. Take, for example, the requirement to construct an effective "semi-infinite" target, one where the rear of the plate does not influence the penetration process. It is



104 Structures Under Shock And Impact

desired to build such a target of rolled, homogeneous armor (RHA) steel. The maximum thickness of RHA commercially available is 20.32 cm. At this thickness, uniformity of material properties is a problem, as is cost. Hence, targets for deep penetration studies are often constructed by using a number of plates of smaller thickness, stacking them until the desired thickness is reached. This target stack is then contained in some fashion (e.g., strapped, welded at the periphery) and the test conducted. In the course of testing the restraints are broken and the front and rear plates are observed to move considerable distances, even for tests involving target plates weighing several tons. Each layer acts as a momentum trap and the outermost layers dissipate the residual energy through rigid body motion.

Several questions must now be answered before the test results may be accepted as valid:

- (a) does the penetration event occur on the same time scale as the rigid body motion of the target plates? In other words, is a layered target an effective simulant of a monoblock target?
- (b) what is the effect of layering as the number of plates required to simulate the monoblock thickness increases?
- (c) if target plates do separate before completion of the penetration/perforation process, what is the effect on the penetration depth (or, if a perforation, on the projectile residual mass and velocity)

These questions must be answered for three classes of targets:

- (a) thin targets ($T/D < 1$ where T = target thickness and D = projectile diameter)
- (b) intermediate thickness targets ($3 < T/D < 10$)
- (c) thick targets ($T/D > 10$)

Thin and Intermediate Thickness Targets

For thin and intermediate thickness targets the answers may be readily inferred from the existing literature. In their study of containment structures, Zaid, El-Kalay and Travis (1973) point out that for very thin plates (thicknesses < 2 mm), lamination greatly reduces the resistance of the target plate to ballistic impact. Netherwood (1979), conducting in situ pressure measurements of impacted plates found the laminated target to be much weaker than a solid one of the same thickness so that the mechanism of penetration of a laminated target was different than that for a solid target. Nixdorff (1984) examined analytically the effect on lamination on the ballistic limit for up to five layers and found considerable differences as the number of layers increased. Similar conclusions were reached by Segletes and Zukas (1989) in a numerical analysis



of laminated plates. Other studies could be cited but these suffice to show that for thin targets, lamination can alter the response mechanism under impact loading and fail to correlate with the behavior of a solid target, especially if the number of layers is large.

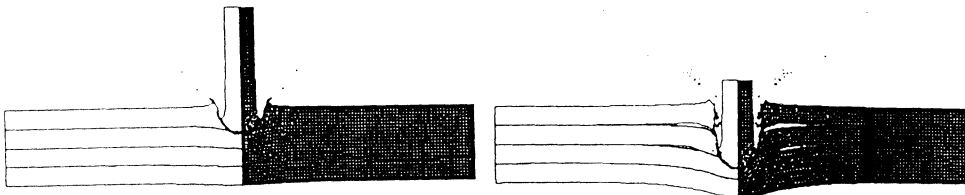
The problem for intermediate thickness targets can be seen from the results of the following calculations. The **Zeus** code [Segletes and Zukas (1987), Janzon et al (1992), Zukas (1993)], a two-dimensional explicit finite element code for fast, transient analysis on personal computers, was used to calculate the impact of a 64.5 gram S-7 tool steel projectile with length-to-diameter (L/D) ratio of 5 into a single RHA plate with a thickness of 3.18 cm. The projectile had a diameter of 1.3 cm and a striking velocity of 1164 m/s. Experimental data was taken from the report by Lambert (1978). The experimentally determined values of projectile residual mass and residual velocity were 22.9 grams and 223 m/s, respectively. **Zeus** calculations indicated a residual mass of 25.5 grams and a residual velocity of 233 m/s. These were deemed acceptably close.

Next, a series of calculations was undertaken where the solid target above was assumed to consist of 2, 4 and 6 layers, each with properties identical to those of the solid target. Penetration of the four-layer target at various times is shown in Figure 1. The variation of projectile normalized residual mass (m_r/m_o) and normalized residual velocity (V_r/V_s , V_s = striking velocity) can be seen in Figures 2 and 3. With the 4-layer laminated target, the difference between Lambert's data for the solid target and the computed residual masses is 43% while for the residual velocity it is 143%. The differences continue to increase with increasing lamination.

Even though the plates making up the laminated target have the same density and material properties as the solid target, the differences noted above could be anticipated. The plates in the laminated target are not restrained and are allowed to slip freely over each other. As they separate after the passage of the projectile, a free surface is created. The inability of a free interface to support rarefaction waves changes the stress wave propagation characteristics of multiplate penetration events at early times. As these stress differences are integrated in time, the difference between the simulations becomes more visible, with the multiplate case demonstrating more bending than the equivalent solid plate case (Figure 4). This can also be inferred from plate theory which gives for the bending stiffness of the plate $ET^3/12(1-\nu^2)$, where E is the elastic modulus, T the plate thickness and ν Poisson's ratio. Since bending stiffness follows plate thickness to the third power, simply cutting a monoblock plate in half reduces its bending stiffness by a factor of 8.



Time = 2.00E-05 4 Layer Plate, Us = 1164 Cycle = 461 Time = 5.00E-05 4 Layer Plate, Us = 1164 Cycle = 1189



Time = 8.00E-05 4 Layer Plate, Us = 1164 Cycle = 1855 Time = 1.20E-04 4 Layer Plate, Us = 1164 Cycle = 2732

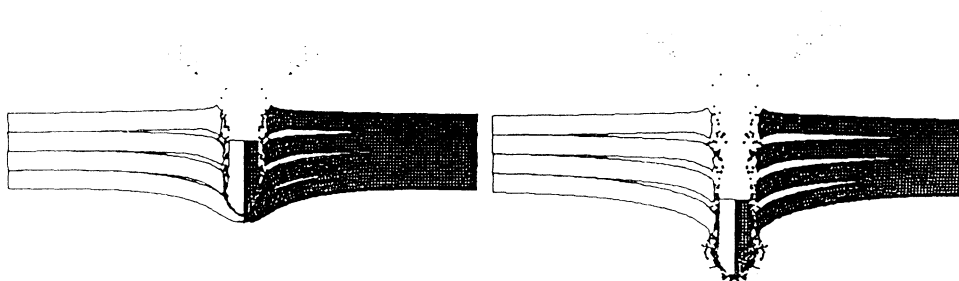


Figure 1. Perforation of a laminated plate

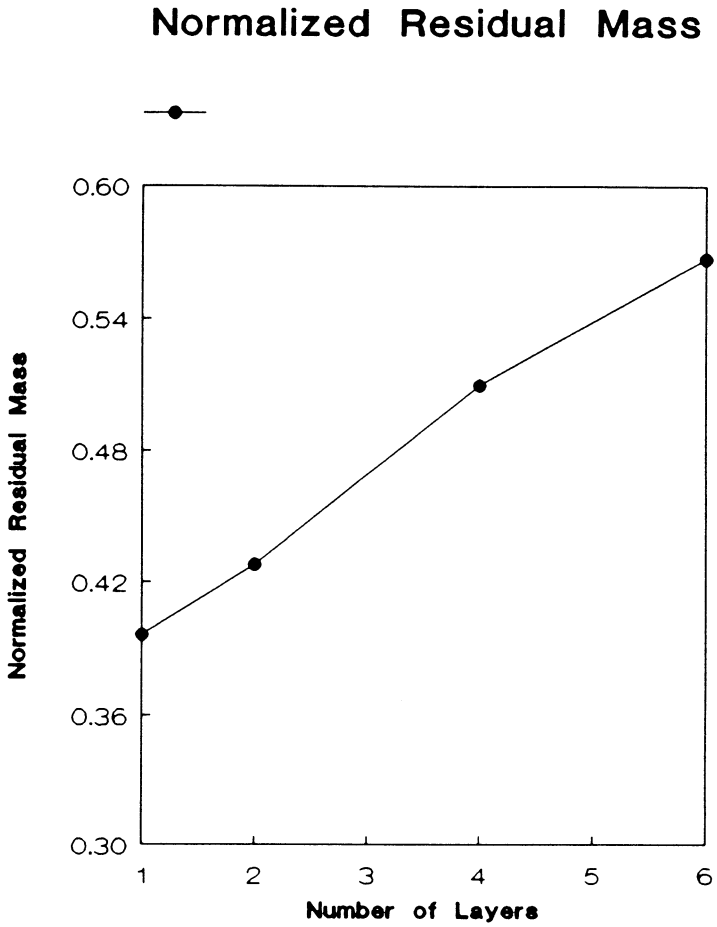


Figure 2. Variation of projectile residual mass with target layering



Normalized Residual Velocity

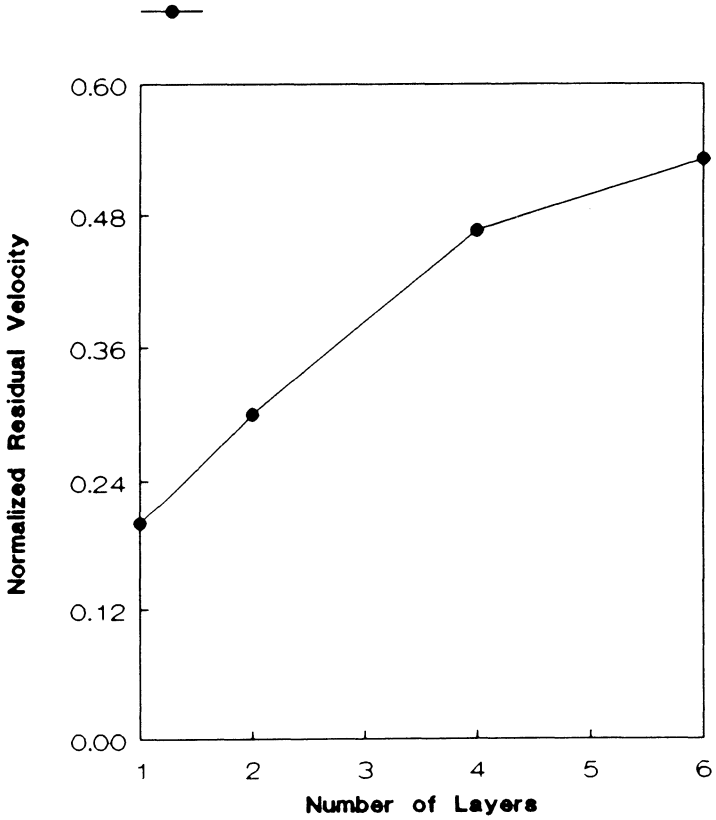


Figure 3. Variation of projectile residual velocity with target layering

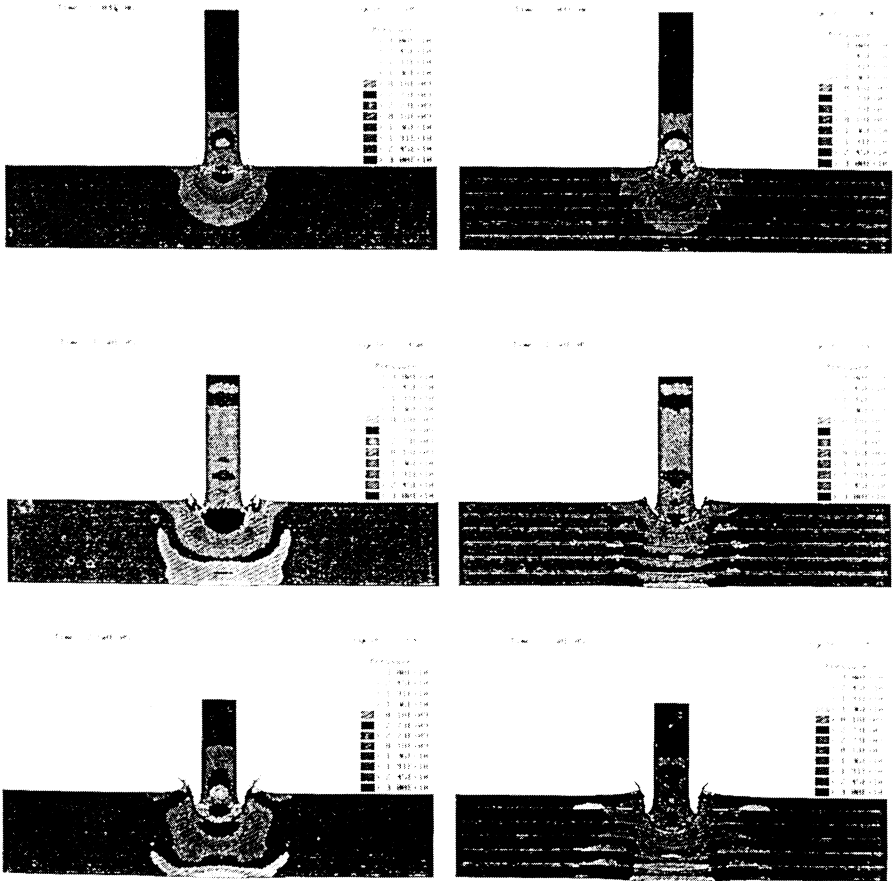


Figure 4. Wave propagation in solid and 6-layer plate



THICK TARGETS

For thicker targets the literature is not as plentiful. The general consensus from laboratories conducting impact tests seems to be that the penetration or perforation event is over before much plate motion occurs; that if the plates are made sufficiently large (in some sense) the event will be over before rarefaction waves return from lateral boundaries and that, on the whole, there will be small deviation from solid target results for results obtained from laminated targets.

To test these assumptions, calculations were performed with plates 15.2 cm thick impacted by long rod projectiles ($L/D=10$) moving at 1500 m/s. In addition to the monoblock configuration, targets consisting of 2, 3 and 6 layers of the same material with the same material properties as the monoblock target were also studied. Figure 5 shows the normalized residual mass results from the calculations. Little difference in residual mass is observed for two and three layers, both increasing somewhat when 6 layers are used to model the target. Similar results hold for residual velocity. This is consistent with the findings of Nixdorff (1984) who found a general decrease in ballistic limit as the number of layers increased from 1 to 5.

For thick targets, the calculations generally confirm that the target remains intact during perforation and that gross plate motion occurs only after passage of the projectile through the bulk of the target. What if this were not the case, though? A calculation was also done allowing spacings of 1 and 4 projectile diameters between plates. Spacing significantly affects the projectile residual mass, as can be seen in Figure 6. However, the size of the gap between plates plays a minor role in determining residual characteristics. Keep in mind, however, that these are very large gaps.

Numerical Considerations

In reviewing these results, a key limitation of code calculations should be kept in mind. Wave propagation codes can be valuable adjuncts to experiments in impact mechanics. However, the principal limiting factor on their accuracy is the modeling of material failure under high loading rates. For isotropic metallic materials, the incremental elastic-plastic constitutive models in most major wave propagation codes, coupled with an equation of state to determine high pressure response, is sufficiently accurate to determine quantities related to displacements (e.g. penetration depths, hole sizes, overall deformation) to within 1-3% of those observed experimentally. Quantities related to velocity (residual velocity, velocity-time histories, momenta, kinetic energy) can readily be determined to within 5%. These accuracies can be obtained provided that the material constants needed for the constitutive model and equation of state are



Thick Layered Target

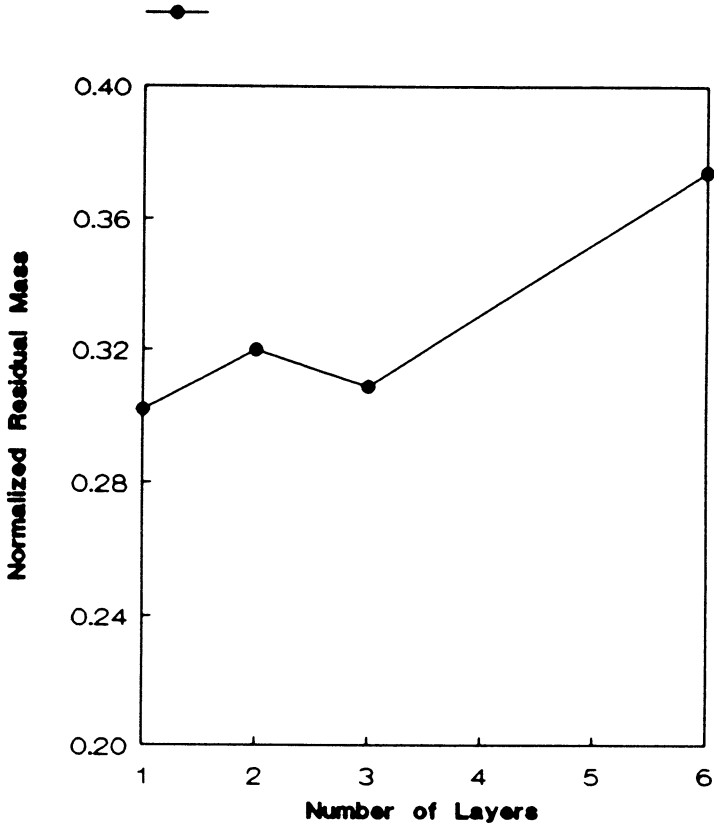


Figure 5. Layering effects in thick targets



Normalized Residual Velocity

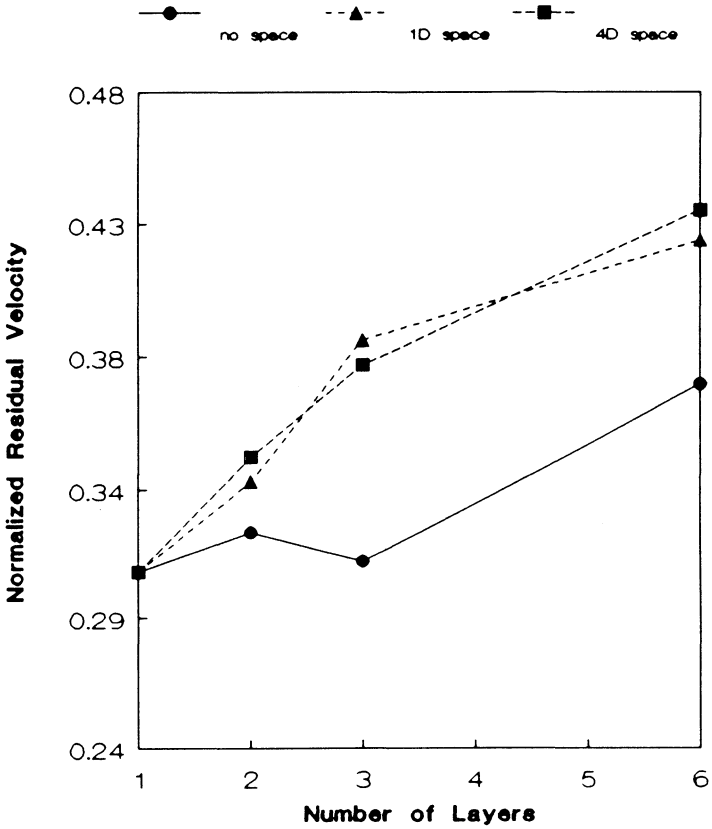


Figure 6. Effects of spacing between target layers



determined from wave propagation experiments at strain rates appropriate to the problem at hand.

Quantities related to mass are affected by a number of conditions, but the most influential of these is the failure criterion used in the calculation. It is now well known that material failure is a time-dependent phenomenon (e.g., Meyers (1994)). However, due to lack of both adequate dynamic failure models and a sufficient data base to drive the few that exist, almost all wave propagation calculations are performed assuming instantaneous failure of a material when a critical value of a key variable is reached. In the **Zeus** calculations cited above, material failure was based on effective plastic strain. When the value of effective plastic strain exceeded 40%, the computational element in which this occurred was no longer allowed to support tensile or shear loading. In effect, it behaved as a fluid transmitting compressive loads only. Once the element's effective plastic strain exceeded some high value (140% in these calculations), the element was removed from the calculation and the erosion/contact processor was called to re-define contact surfaces. Since element nodes are never removed from a calculation, mass and momentum are conserved throughout. However, once an element is removed, its internal energy is no longer tracked so that energy is conserved only approximately. **Zeus** therefore keeps track of the ratio of total to internal energy, E/E_0 . During these calculations, this ratio did not vary by more than 1%.

The net result of these approximations is that quantities affected by the failure criterion and the erosion processor are accurate to, at best, 10%. Thus, a statement here that the normalized residual mass for a given calculation was 0.302 would mean that the same quantity, determined experimentally, would fall somewhere between 0.29 and 0.32. Specifically, consider Figure 7, which shows the data of Figure 6 in a different form. For the 6 layer case, the normalized residual projectile mass difference between a target with no gaps and one with a spacing of 4 projectile diameters is about 17%. Taking into account the accuracy of the calculations as regards eroded mass, one would expect that the observed differences from a number of experiments would range between 12 - 22%. These calculations satisfy the conservation equations, account for the intricacy of multiple wave reflections in complex targets and so accurately model inertia effects. One can expect then that trends are accurately portrayed but that the actual numbers computed for mass quantities will vary by 10% or more if comparable experiments were carefully performed.

Conclusions

Layering dramatically weakens thin and intermediate thickness targets. For very thin targets, even the mechanism of penetration may change. Thick targets, however, show very small changes in projectile residual properties and, if proper care is taken with regard to material properties and target assembly,



Effect of Spacing

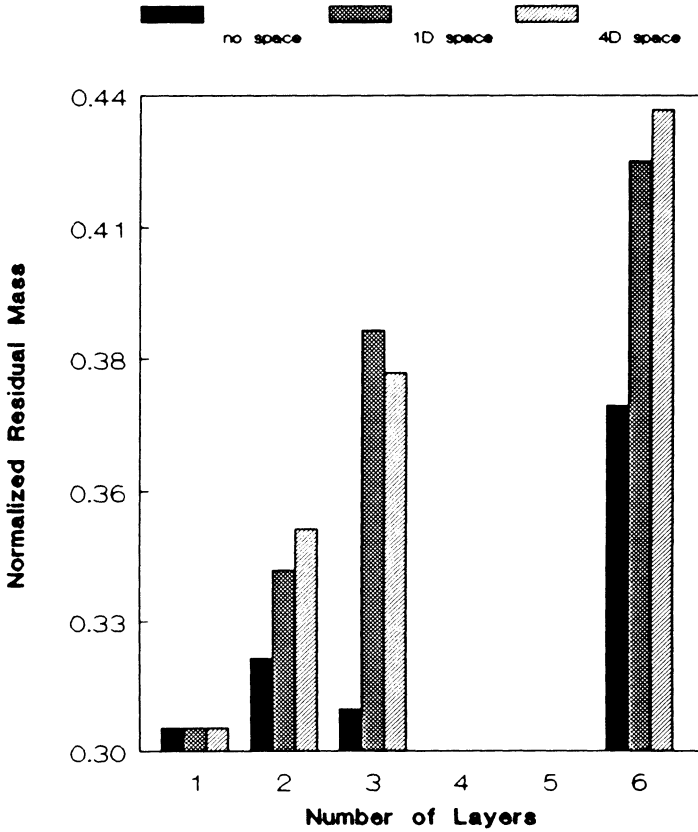


Figure 7. Alternate view of spacing effects on residual mass



laminated thick plates can effectively simulate results obtained from equivalent solid targets. Care must be taken to avoid gaps between plates, either initially or during the perforation process. Individual target layers should also be treated, if need be, to insure that their properties correspond to those of an equivalent monoblock target.

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