Study of Blast Wave Mitigation Barriers Using Steel Angles with Various Short/Long Arrangements

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***Abstract*—The renewed patterns of barriers to protect infrastructures are required against the advanced styles of terrorist attacks. The wave interference concept is the base for the fence type barriers to be useful to mitigate the blast loads effects. In this paper, the performance of six short/long arranging of steel angles' rows is compared to each other. The main concern is oriented to analyze the results of the mid-height level gauges' positions. While comparing systems, the total weight of systems is maintained constant. The mitigation percent criteria mathematical method is employed to compare the rows' systems mitigation percentages. The parametric studies disclosed that double rows system is better than a single one, therefore, the double rows cause the increasing of the reflected wave which enhances the mitigation percentages. Double long rows system achieves the most powerful attenuation to impulsive forces and satisfies a noticeable decrease for the peak overpressure. Using single or double short steel angles' row slightly enhances the mitigation percent especially at the mid-height gauges. The results concluded that using double rows system that includes one or both long rows is a more powerful fence to satisfy higher impulse mitigation percentage for humans and the structure as well.**

***Index Terms*—blast mitigation, blast barriers, protection system, mitigation percent, protection evaluation**

I. Introduction

Terrorist attacks became a serious problem to take into consideration while building and/or protecting infrastructures. The advanced styles of terrorism need renewed patterns of mitigation fences to protect important buildings against blast loads. Many researchers have studied blast loads' effects on buildings and the new applicable techniques to attenuate or even prevent the effects at the buildings under consideration. A large amount of literature has been presented to design and analyze different types of fences against impacts due to the blast loads. The attenuation system placed in front of structures to mitigate the generated blast wave is one of the strategies commonly used for structural protection. Researches have been implemented to offer computation equations, charts and empirical formulas which can be helpful for researchers to achieve suitable mathematical methods to measure the structural response. Then, blast-resistant structural design subjected to blast loads, and various attenuation systems can be built [1-3].

S. Berger et al. [4-6] studied a shock wave undergoing through obstacles on the center of the end-wall of a shock tube. They inferred that the effect of the geometry is overriding and the wave mitigation effect is more evident for general geometries. They investigated the mitigation mechanism and the interaction of blast waves with barriers of different sizes and shapes to deduce the dependence of the shock wave attenuation on barrier geometries. R. Hajek and M. Foglar [7-9] investigated the interaction between the blast load and the ambient structures. They studied the shock wave attenuation at the barrier surface and examined the behavior of different shaped rigid barriers due to the propagation of blast wave. The effect of the wave pressure decreased to almost its original capacity for higher distances.

Fence type blast wall is widely studied to take place of the solid wall to mitigate the blast loads based on the concept of wave interference. This type of fence is formed of columns of available materials structurally arranged as wave obstacles. Different arrangements give rise to wave reflection, diffraction, and interaction between them which leads to a noticeable reduction in the blast wall effects. D. Asprone et al. [10, 11] studied a discontinuous GFRP barrier as a fence system for important buildings by simulating blast tests with detailed

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numerical and experimental analysis. They described results of the blast test crackdown carried out at full-size specimens of the proposed barrier and analyzed the effect in mitigating blast shock waves.

A. Hadjadj et al. [12, 13] deduced wave phenomena generated by large scale explosions in complex environments. They described the complex flow field caused by blast and shock waves that pass through sophisticated media to design new appliances for protection against blast loading. They analyzed numerically shock-wave propagation through different arrangements of solid obstacles and their mitigation effects. The staggered matrix of the reversed triangular prism and the combination arrangement of triangular prism obstacle is found to be more powerful in blast wave attenuation. Y. Hao et al. [14] Studied combined structural columns with circular and triangular cross-sections as fence blast walls and investigate field tests to deduce that the double-layer staggered arrangement outperformed the other tested systems.

The mechanical domination is the most powerful and dependable control [15, 16]. Weifang Xiao et al. [17, 18] show a new method to deduce the efficient of various blast wall configurations in achieving protection against blast loads. They found that certain blast wall arrangement can decrease the blast effects on structures. They investigated the protection power of the barrier made of steel posts with different hollow cross-sections. They compared numerical and experimental investigations on the shock wave attenuation effect of the different arrangements of barriers.

In this work, steel barriers with various short/long arranging of rows are proposed as blast load attenuation systems. Numerical discussions are applied to find out the results of the mid-height level gauges' positions, that represent the human locations behind the protective layer. A single baseline one row of conventional attenuation system (short height and long height) is drawn up through the application of the state of the art in this field and compared with other various short/long double rows' systems. The total weight of each steel system's rows is maintained constant. Comprehensive parametric studies are used to measure and discuss the responding of the systems under investigation.

II. Characterization of Attenuation Systems

A reference system has been taken from the literature [14]. The dependable barrier system consists of two staggered triangular elements' rows. The stiffness of the attenuation system of rows is the main point to mitigate blast loads' effects in front of the targeted structure. It is proposed to investigate double rows' arranging of short/long rows of steel barriers and analyze its stiffness in contradiction to each other to deduce the efficiency of the blast waves attenuation. Also, the system's ability to absorb the residual of blast wave strain energy due to its high stiffness. Six short/long arranging of steel angles' rows are taken into the investigation. One short row (R-S0), one long row (R-L0), two short rows (R-SS), two long rows (R-LL), two rows with short front and long rear (R-SL), and two rows with long front and short rear (R-LS). Short rows are 2 m height and long rows are 4 m height. The steel angles' elements are with cross-section dimension 180 × 180 mm and the inner of the angle faces the blast waves. The lateral spacing between two adjacent angles equals 50 cm (angle center to angle center). The thicknesses of the rows are distributed between 16 mm, 8 mm, and 4 mm as illustrated in Fig. 1 to maintain the same weight 180.40 kg/ line meter for all proposed systems. For the two rows' systems, the longitudinal spacing between the two rows is 1 m.

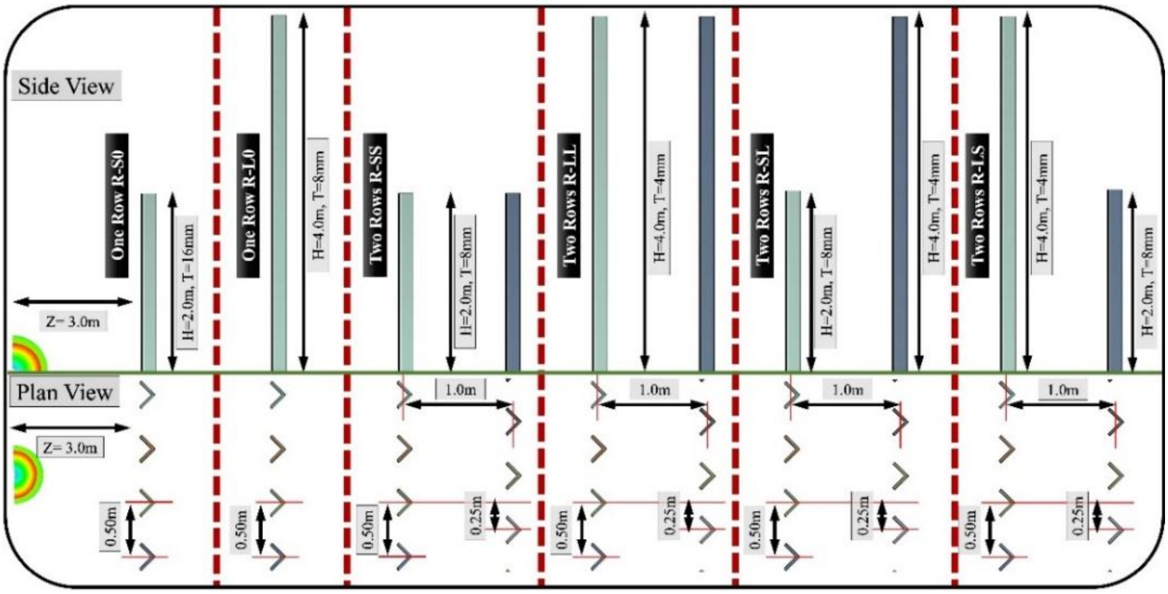

Figure 1. The general Arranging of the compared six systems

III. FE Modeling and Systems' Properties

The commercial software AUTODYN is used to configure the numerical simulations. For parametric studies, the TNT charge weight is 100 kg (Small utility/pickup) [19], with reference density 1.63 g/cm^3 along with auto-convert to an ideal gas. Air is assigned as an ideal gas equation of state, and the steel used in systems' simulations is STEEL_4340. Four virtual pressure gauges are considered to numerically measure the blast pressure time histories of the studied zone for the 3D boundaries. Its dimensions are G#1 (0,0,6), G#2 (0,0,9), G#3 (2,0,6), and G#4 (2,0,9), where the level from the ground surface is the (X) coordinate and the standoff distance from the detonation origin point is the (Z) coordinate. The coordinates of the four gauges are selected due to TNT charge origin position, O (0,0,0). All these locations are shown in Fig. 2 as configured in the AUTODYN' simulations.

The pressure and impulse time-histories of G#1 and G#2 are compared as shown in Fig. 3 and Fig. 4, respectively. The real percentage of the boundary conditions and the generated impulse are checked. The impulse equals the area under the curve related to the zero pressure datum. For no mitigation system, the pressure gauges' reading is assigned as the reference that has zero percent of attenuation. So, any attenuation percent is calculated as a ratio of that zero reference.

Mitigation percent criteria is the mathematical method to calculate the impulse percentage for the systems [20]. The trapezoidal rule is utilized to integrate the pressure gauges' reading curves and calculate the impulse.

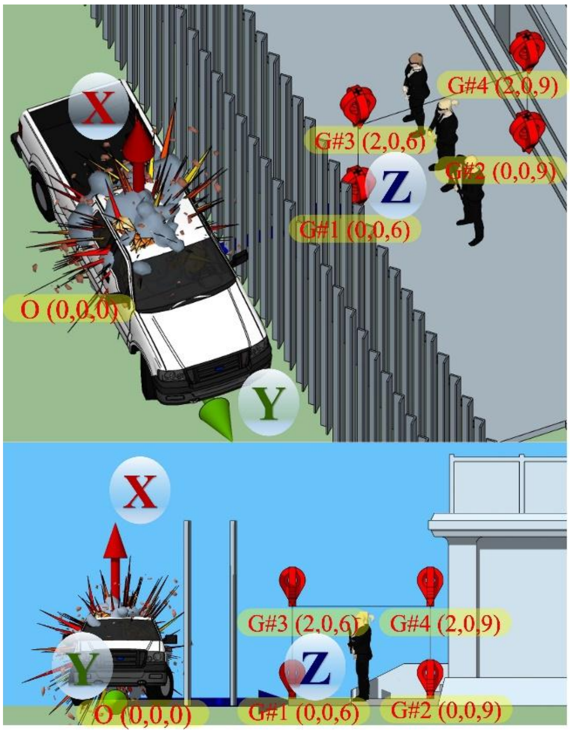

Figure 2. The virtual pressure gauges' coordinates.

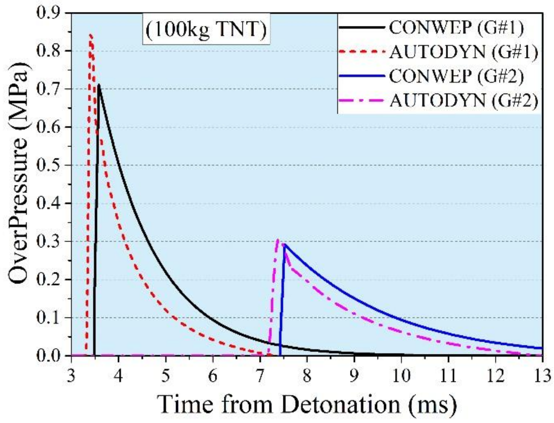

Figure 3. Pressure time-histories of G#1 and G#2

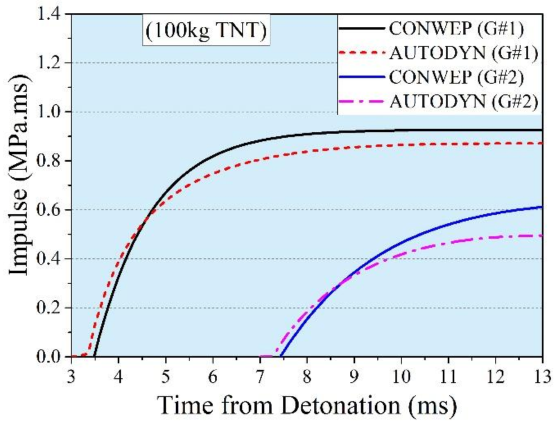

Figure 4. Impulse time-histories of G#1 and G#2

The time subinterval is $t_k \in [0, 20]$ such that $t_0 = 0 \prec t_1 \prec .... \prec t_{N-1} \prec t_N = 20$, and $\Delta t = t_{k+1} - t_k$ then:

$$II_{no\_mit} = \begin{cases} \lim_{\Delta t \to 0} \sum_{k=1}^{N} \left(\frac{(P_{no\_mit})_{k+1} + (P_{no\_mit})_k}{2} \right) \times \Delta t & \text{if } P_{no\_mit} \succ 0 \\ 0 & \textit{otherwise} \end{cases} \quad (1)$$

$$II_{Rows} = \begin{cases} \lim_{\Delta t \to 0} \sum_{k=1}^{N} \left(\frac{(P_{Rows})_{k+1} + (P_{Rows})_k}{2} \right) \times \Delta t & \text{if } P_{Rows} \succ 0 \\ 0 & \textit{otherwise} \end{cases} \quad (2)$$

Where

P_{no_mit} ….. scored pressure in no mitigation case.

P_{Rows} ….. scored pressure in mitigation systems.

II_{no_mit} ….. the sum of no mitigation case's Impulse.

II_{Rows} ….. the sum of mitigation systems' Impulse.

And so, equation (3) is used to calculate the mitigation percentage criteria to compare the systems. The results of equation (3) are shown by the columns in Fig. 9.

$$\text{Rows Mitigation Percentage} = \left[1 - \frac{II_{Rows}}{II_{No\_Mit}} \right] \% \quad (3)$$

IV. Results and Discussion

The pressure-time history readings of the 100kg TNT for standoff distance Z=6m at G#1 and G#3 are represented at Fig. 5 and Fig. 6 respectively. Also, the pressure-time history readings of the 100kg TNT for standoff distance Z=9m at G#2 and G#4 are represented at Fig. 7 and Fig. 8 respectively.

For all gauges' positions, it can be deduced that double rows systems are more powerful fence than single rows systems to satisfy higher impulse mitigation percentage for humans standing behind the fence and the structure as well. R-SS mitigation system satisfies good attenuation for G#1 position, but slightly enhances the mitigation percent for other gauges' positions especially at the mid-height gauges in compared to the investigated double rows systems.

R-LL mitigation system achieves the most vigorous attenuation to impulsive forces and satisfies a noticeable decrease for the peak point overpressure at all gauges' positions. R-SL mitigation system can achieve a sensible attenuation. But, R-LS mitigation system shows weaker mitigations than those. Using single short steel angles' row as a fence doesn't show good supportive effects of attenuation for all gauges' positions.

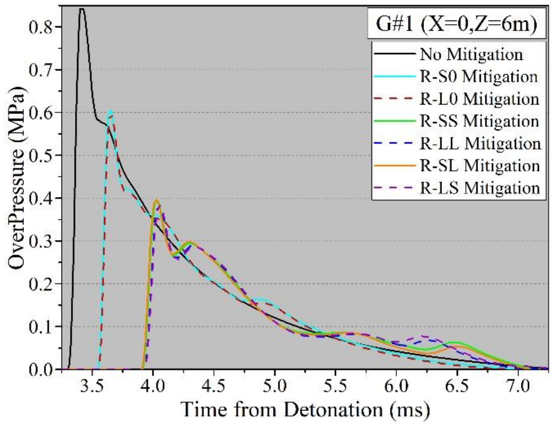

Figure 5. Pressure-time history readings at G#1.

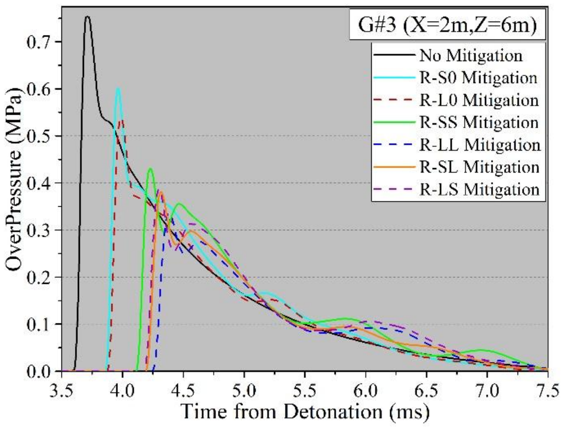

Figure 6. Pressure-time history readings at G#3.

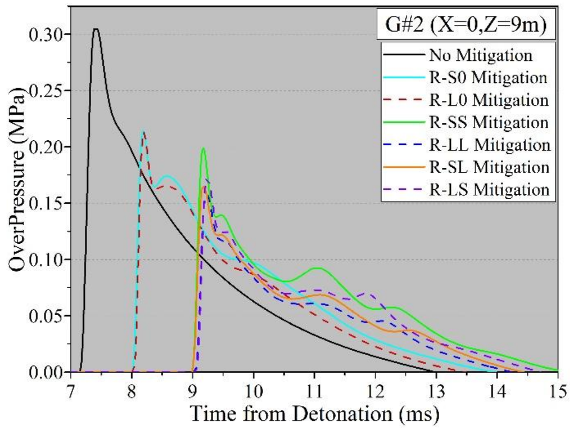

Figure 7. Pressure-time history readings at G#2.

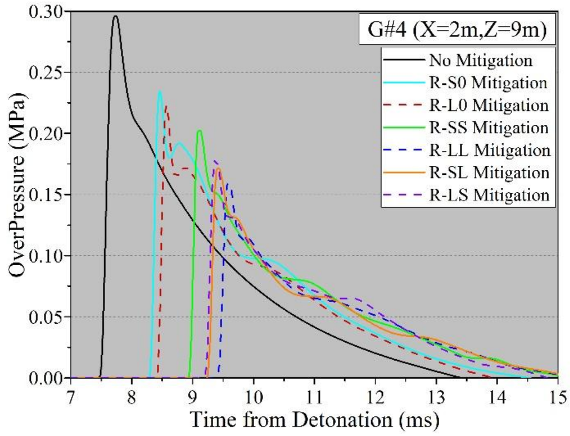

Figure 8. Pressure-time history readings at G#4.

The percentages of blast pressure mitigation for the six compared systems are illustrated by Fig. 9.

The pressure history of the R-LL mitigation system and its distribution are clarified by contour lines chart at Fig. 10 with an adapted scale at time T=2.5ms.

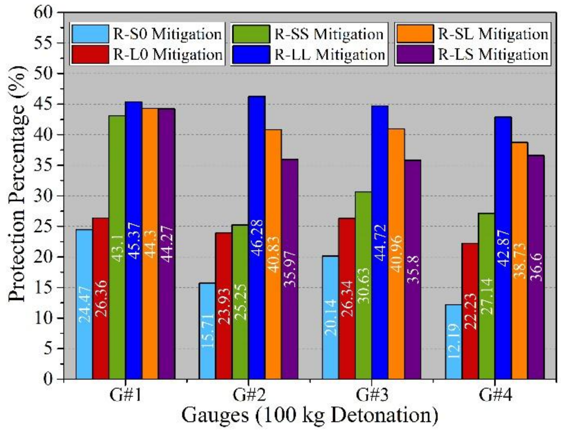

Figure 9. Relative impulse mitigation percentage for the six compared systems

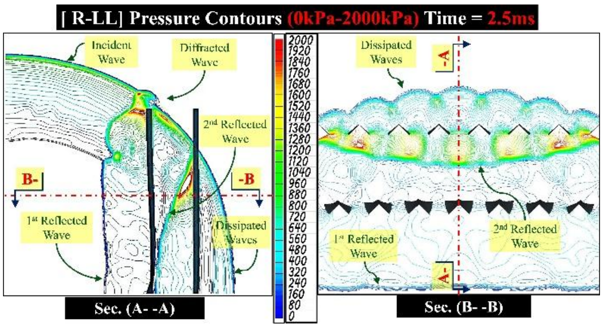

Figure 10. The pressure history of the R-LL system and its distribution

It can be noticed that the blast wave propagation starts at the center of the detonation position and directs towards R-LL system place. The pressure contours demonstrate that the front waves override the first row of the barrier and dispel across in between the second row's gaps. The blast wave partitions are showed up as an incident wave, diffracted wave, and dissipated wave in diverse directions. Behind the rows, the diffracted and dissipated waves are re-stacked, which cause a relative average reduction of the blast wave mitigation percentage, especially at G#4 position (the mid-height level of the system). The interaction shown explains the reason that R-LL mitigation system can satisfy the most powerful attenuation to impulsive forces to protect humans and targeted structure, in comparison to the other investigated mitigation systems.

The pressure history of the six compared systems and its distribution represented by contour lines chart are indicated in Fig. 11.

It can be concluded that using double rows systems instead of single row systems cause the increasing of the reflected wave which can enhance the barrier system's mitigation to attenuate blast waves and reduce wave effects behind the barrier at humans or targeted structure.

Also, the investigated barriers systems which contain short steel angles' rows did not show good supportive effects for these systems, especially at the mid-height level gauges' positions G#2 and G#4.

V. Conclusions:

In the present paper, numerical discussions are provided to discuss blast load steel barriers with various short/long arranging of rows. The suitable attenuation arranging of rows to be a good protecting barrier for behind humans and targeted structure is the target of the investigation. The performance of six short/long arranging of steel angles' rows is compared in contradiction to each other through comprehensive parametric studies. The total weight of each steel system's rows is maintained constant. The main conclusions for the investigation are summarized below:

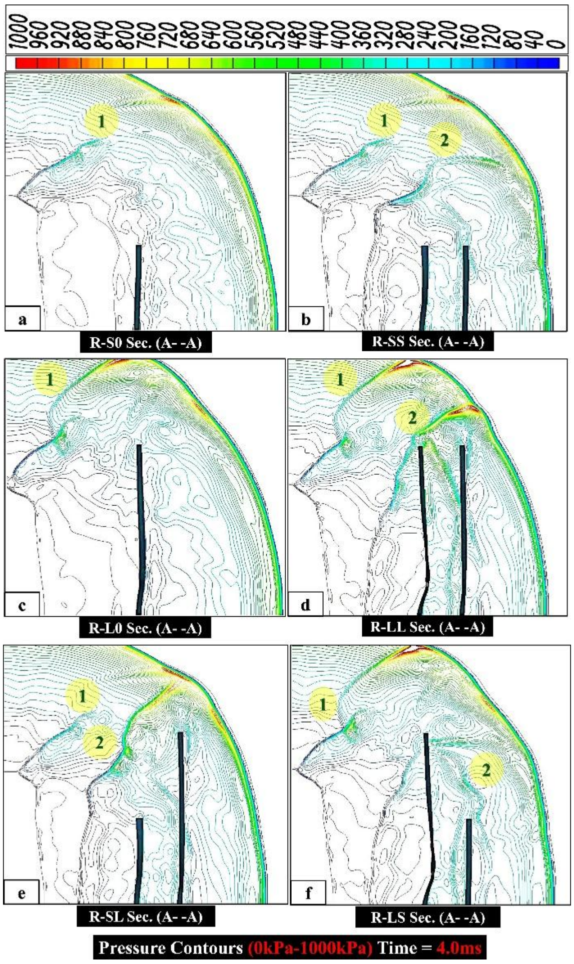

Figure 11. The pressure history of the six compared systems and its distribution

- Using the double rows systems cause the increasing of the reflected wave which can enhance the barrier system's mitigation to attenuate blast waves effects behind the barrier.
- R-LL mitigation system, in comparison to the other investigated systems, achieves the most powerful attenuation to impulsive forces and satisfies a noticeable decrease for the peak point overpressure at all gauges' positions.
- Using single short steel angles' row as a fence doesn't show good supportive effects of attenuation for all positions. adding another short row.
- Adding another short row (R-SS system) can satisfy a remarkable attenuation to impulsive forces only for G#1 position, but slightly enhances the mitigation percent especially at the mid-height gauges G#2 and G#4.
- The double rows systems are more powerful fence than single row systems to satisfy higher impulse mitigation percentage for humans standing behind the fence and the structure as well.

Conflict of Interest

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors had shared in all contributions and steps to prepare this work; all authors had approved the final version.

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