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Economical seismic retrofit schemes for vulnerable RC buildings with infill-brick wall using new FRP technologies

B.Binici[1] and K. Kobayashi[2]

[1] *Associate Professor, Dept. of Civil Engineering, Middle East Technical University, Turkey*
[2] *Professor, Dept. of Architecture and Civil Engineering , University of Fukui, Japan*
Email: binici@metu.edu.tr , katsumi@anc.anc-d.fukui-u.ac.jp

ABSTRACT :

The idea of using FRPs for seismic retrofit of hollow brick infill walls of deficient RC frames was developed within the last decade. In those studies, surface bonded FRPs acting as cross braces integrated to the boundary frames were effective in increasing lateral strength. Keeping in mind that one of the most important issues is the cost effectiveness, more economical solutions with new FRP technologies can be employed. The concept of "sewing bands" emerged at this point for the seismic retrofit of initially for RC shear walls and later for RC frames with hollow brick infill walls. The applicability of sewing bands for seismic retrofit of deficient RC frames with infill walls was found to be promising. In this study, we present cyclic diagonal compression test results of brick infilled RC frames retrofitted with "sewing bands". A simple design oriented mechanical model was developed to simulate the load-deformation response of the test specimens. Experimental results from diagonal compression tests reported herein and cyclic lateral displacement tests presented previously are compared with the model estimations. A reasonable agreement was observed between test results and model estimations showing that the model can be used in seismic strengthening of infill walls with sewing bands.

KEYWORDS: Sewing band, FRP, brick infill wall

1. INTRODUCTION

With recent earthquakes occurred in the world (Kocaeli-Turkey 1999, Sumatra-Indonesia 2004, Ika-Peru 2007, etc.), the vulnerability of the 20 to 30 year old building stock is once again revealed before the eyes of the structural engineering community. Earthquake reconnaissance surveys showed that there is a significant number of reinforced concrete frames with infill walls within the mid-rise deficient building stock. Infill walls, used generally as partitions between rooms, contribute to lateral strength at low deformation levels (i.e. below 1% lateral drift ratios). However, they became precarious at larger deformation levels due to the risk of out of plane collapse. Hence, rapid, reliable, economical and user friendly retrofit schemes for these deficient RC buildings are needed to mitigate the seismic hazard.

Use of fiber reinforced polymers (FRPs) in the upgrading of reinforced concrete frames with infill walls was developed as a part of an extensive research project (Ozcebe et. al. 2003). The method was based on the premise of limiting inter-story deformations and increasing the base shear capacity of the existing weak frame using FRPs bonded on the surface of infill walls integrated to the boundary frame members with FRP anchors. Quasi-static cyclic tests were performed on multi-bay multi story structures in order to experimentally validate the effectiveness of the FRP strengthening system (Erduran 2002 and Akguzel 2003). The proposed method was found to be appealing due to its speed and ease of application with little or no disturbance to the occupants. Subsequently, an analytical model that is capable of estimating the nonlinear static response of the FRP strengthened infill wall was proposed (Binici and Ozcebe 2006).

The most important disadvantage of FRP cross-braces as an alternative to more conventional retrofit schemes (for example addition of shear walls) is the cost effectiveness. In order to overcome this deficiency, the ideas borrowed from FRP stitching of RC slabs for punching shear strengthening (Binici and Bayrak, 2003) was applied to strengthen RC shear walls (Kobayashi, 2005) and brick infilled RC frames (Kobayashi, 2007). The most important observation, reported by Kobayashi (2007), was the fact that appropriate volume of sewing bands can help to increase deformability of the wall. More importantly, sewing bands can act as elements that can keep the wall intact for in and out of plane deformations.

In order to further investigate the influence of fiber strand volume on the strength and deformation capacity of the compression strut, cyclic diagonal compression tests were conducted. This study presents the summary of experimental findings and a simple analytical model to explain the force transfer-deformation relationship for sewing bands.

2. EXPERIMENTAL PROGRAM

1.1. Introduction

Four specimens were tested in the experimental program. The brick infill wall specimens were built together with the boundary frames to realistically simulate the interaction effects of the walls and frames. Hollow bricks used for the infill walls were made of dental gypsum, overall dimensions of the test specimen and details testing are shown in Fig. 1. Main test parameter in the experimental investigation was the use different amount of fiber amount (i.e. specimens 1, 2, 3, and 4 were strengthened with 1, 2, 4, and 8 aramid fiber strands).

Sewing band application can be summarized as follows: First, holes are drilled at certain intervals on the brick joint lines in both horizontal and vertical directions. Then, a bundle of strands with resin are put through the holes forming a sewing path as shown in Fig. 2. The end of strands is wound around the columns to secure the anchorage of the end of sewing bands and to increase the shear capacity of columns. No surface preparation of the infill wall is needed during the application of the sewing bands, hence making the installation process of fiber strands very easy and economical.

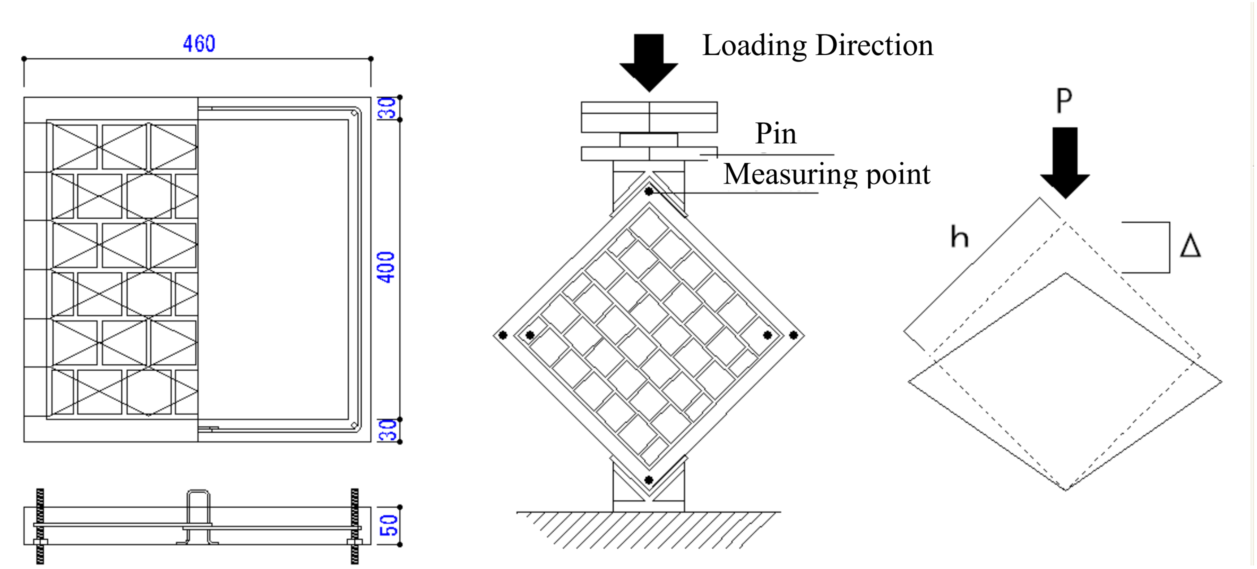
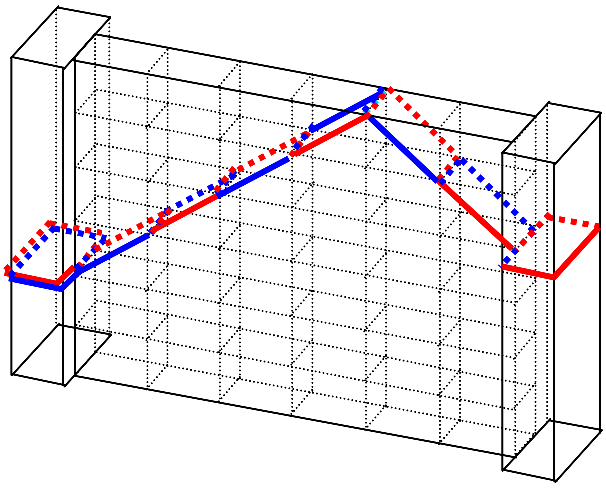


Figure 1. Specimen Details and Testing



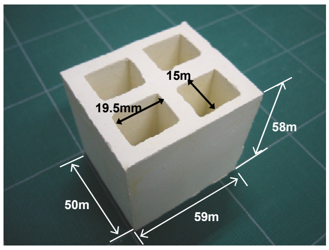


Figure 2. Application of Sewing Bands

Table 1.1 Summary of Material Properties

Material Name	Young's modulus (MPa)	Yield strength (MPa)	Compressive strength (MPa)	Tensile strength (MPa)
Aramid Strand with Sectional area of 0.59 mm^2	98000			2916
Infill Brick	3000		14.4	
Steel Bar (ϕ4) in the frame	210000	265		364.5
Joint Mortar			7.91	
Mortar (boundary frame)			10.8	

Mechanical properties of the materials used for the test specimens are presented in Table 1. Specimens were tested under a stiff loading machine (Fig. 1). Compressive loading and unloading displacement cycles were imposed along the diagonal direction of the test specimens. Diagonal deformation, Δ, was measured and load-displacement responses of specimens were obtained.

1.2. Experimental Results

The experimentally obtained relationships between the applied load, P, and the diagonal displacement, Δ, are presented in Fig. 4. Specimen pictures at the end of the tests are presented in Fig. 5. The behavior of all the specimens was nearly elastic up to a diagonal displacement of about 0.6 mm, which corresponds to an average diagonal strain of about 0.0015. For specimen 1, the opening of vertical joint became visible at a load of 15 kN. After that, applied load remained almost constant up until diagonal displacement was 3 mm. Beyond this point, sewing bands started contributing to the load carrying capacity by limiting crack opening displacements. The maximum load achieved for this specimen was about 21 kN. If the cracking capacity of the infill panel is accepted as 15 kN, contribution of one strand sewing bands to load carrying capacity can be calculated as 6.8 kN for specimen 1.

For specimens 2 and 3, the increase of load carrying capacity beyond a diagonal displacement of 0.6mm was proportional to the amount of strand in a sewing band. In other words, use of two strands provided a strength increase of about 9.5 kN. This increase was about 18 kN for specimen 3. Maximum load carrying capacities of specimens 2 and 3 were reached at a displacement of about 3 mm. For specimen 4, initiation of diagonal crushing of the infill wall started to occur at about 3mm diagonal displacement.

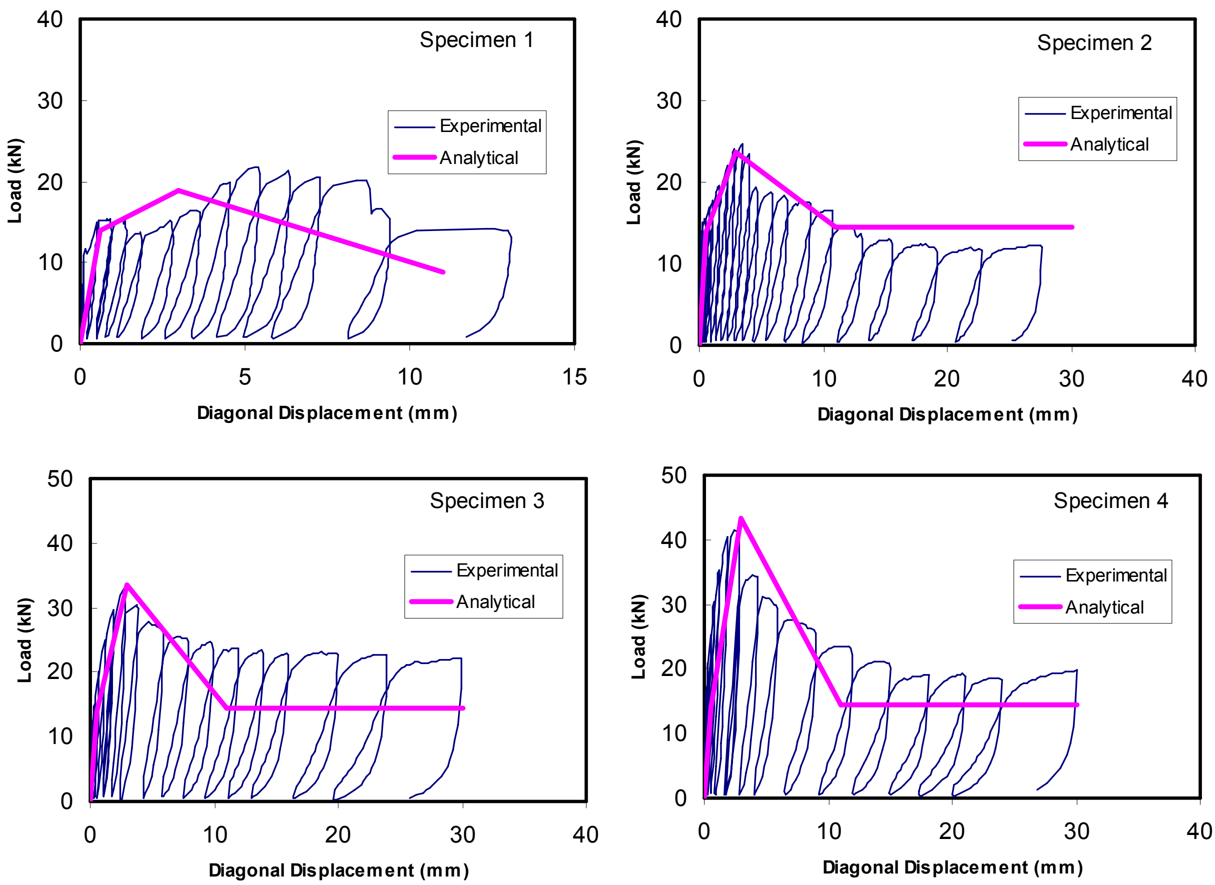
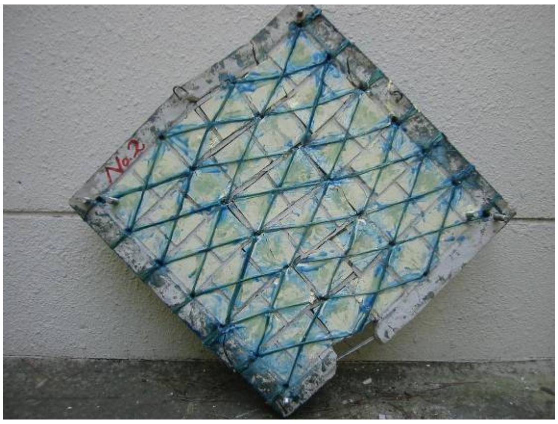


Figure 4. Experimental and Analytical Load Deformation Response of Test Specimens

a) Specimen 1



b) Specimen 2

c) Specimen 3

d) Specimen 4

Figure 5. Failure modes of Test Specimens

Upon reaching the maximum loads, responses of all the specimens exhibited a softening region with a residual capacity. Residual capacities of the specimens were reached at about a displacement of 11 mm and ranged from 13 to 23 kN depending on fiber strand amount.

Test results reveal that main beneficial effect of the sewing bands is delaying crack opening and contribution to load carrying capacity by keeping the infill wall intact. In addition it can be stated that the use more fiber strands can result in higher capacity enhancements and residual capacities.

3. A SIMPLE ANALYTICAL MODEL

From the test results presented in Fig. 4, it can be observed there are mainly three regions for the load-deformation response of infill walls with sewing bands. First region is the elastic region up to cracking. At this stage, bed joint mortar tensile strength is reached and upon cracking there is a reduction in the stiffness of the system. Second region, is the post cracking region. In the case of infill wall with no sewing bands, strength can be maintained up until frictional resistance is completely overcome. For the case of infill wall with sewing bands, further load carrying capacity is available due to the contribution of tensile strength of fibers and their ability to limit crack openings in the mortar joints. The third region is the softening region of the load-deformation response. At this stage frictional strength of the mortar bed joints tend to decrease and crack opening and propagation are observed. For infill frames with no sewing bands, load carrying capacity reduces to zero. On the other, infill walls with sewing bands, the wall can further carry load due to tensile strength of fiber strands leading to available residual carrying capacity.

Based on these observations, load deformation response of the infill wall can be modeled with a simple mechanical model composed of a horizontal spring with experimentally calibrated load-deformation response. The schematics of the model and the proposed load-deformation response for the infill wall are shown in Fig. 6. The cracking load, P_{cr} of the infill wall can be estimated by:

$$P_{cr} = 0.35\sqrt{f_{cm}}\,b\,t\cos\theta \tag{3.1}$$

where f_{cm} is the compressive strength of the mortar bed joint, b and t are the width and thickness of the wall respectively. For the infill walls with sewing bands, ultimate load carrying capacity is the smaller of two capacities controlled by FRP amount and crushing strength of the infill wall:

$$P_u = \min(0.15 f_c b t,\; P_{cr} + 0.015\, n\, E_f A_f \cos\theta) \tag{3.2}$$

In Eqn 3.2, is f_c the compressive strength of the brick infill, n, E_f and A_f are the number of fiber strands crossing the horizontal joint line, modulus of elasticity and cross sectional area of fiber strands, respectively, and θ is the angle of the sewing bands with the horizontal bed joints. Eqn. 3.2 proposes that increasing the amount of fiber strands is beneficial up to a certain capacity at which crushing of the brick infills govern the capacity of the wall.

The residual capacity of the infill walls with sewing bands, P_r can be computed by using Eqn. 3.3.

$$P_r = \min(0.05 f_c b t,\; 0.9\, n\, A_f \sigma_f \cos\theta) \tag{3.3}$$

in which σ_f is the tensile strength of the fibers. Based on the limited number of experiments, corresponding displacement levels, Δ_{cr}, Δ_u, and Δ_r are determined as 0.6 mm, 3 mm, and 15 mm, respectively. In general use of strain values are more appropriate when the wall dimensions are different than those of the test specimens. Hence, corresponding strains for these deformation levels can be computed by dividing the above given horizontal joint displacements by the wall length (400 mm), and they are found as 0.0015, 0.0075, 0.0275, and 0.075.

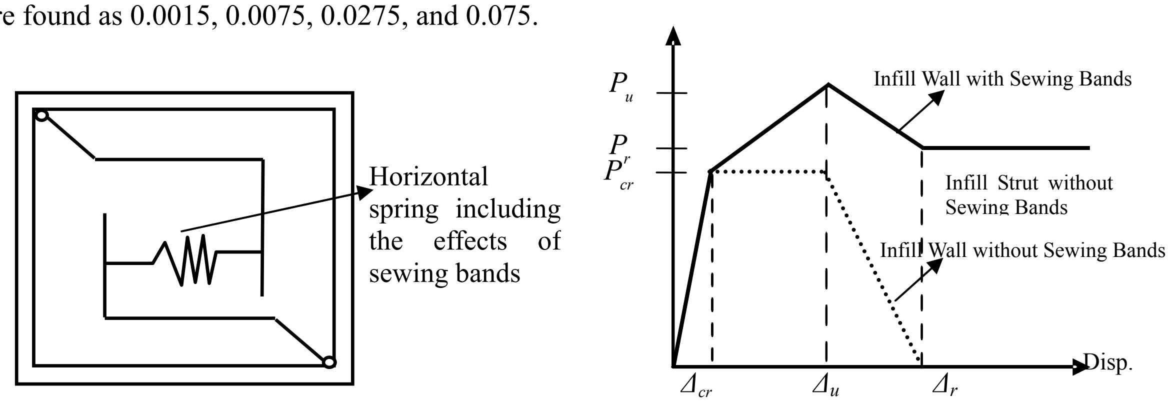


Figure 6 Simple Mechanical Model with Assumed Load Deformation Response

Estimations of the load-deformation response of the test specimens are presented in Fig. 4. It can be observed that there is a reasonable agreement between model predictions and test results. Residual capacities are slightly underestimated for Specimens 3 and 4, whereas the agreement is excellent for Specimen 2. For Specimen 1, the model is capable of estimating the general trend of the load-deformation response with slightly underestimating the ultimate capacity. In general, it can be stated that model predictions are safe when compared with the experimental results.

Further verification studies were conducted using the experimental results of frame specimens tested by imposing lateral displacement excursions. The test setup and dimensions of the specimens are presented in Fig. 7. The details of the test results are presented elsewhere (Kobayashi 2007). Cyclic lateral force deformation response of test specimens along with estimated monotonic capacity curves obtained using the proposed model are shown in Fig. 8. It should be noted that the curve describing the horizontal capacity values, P_{cr}, P_u, P_u are computed using Eqns. 3.1 to 3.3 and displacement values, Δ_{cr}, Δ_u, and Δ_r are computed from the strain levels proposed in the above model (i.e. they are taken as 1.2 mm, 6mm, and 22mm, respectively). Estimated monotonic capacity curves for the bare frame and frame with infill wall are presented in Fig. 8. It can be observed that use of sewing bands contribute to lateral load carrying capacity and enhance the deformability of the system. Furthermore, estimations obtained by using the proposed model are reasonably accurate in estimating the capacity of the specimens and it can be used in seismic evaluation and strengthening designs using inelastic procedures.

3. CONCLUSIONS

In this study, we report on diagonal compression experiments of infill walls strengthened using sewing bands. A simple macro model is proposed to estimate the load-deformation of the test specimens and hollow brick infilled RC frames strengthened with sewing bands. The fact that strength enhancement being limited with the diagonal crushing of the infill walls is also accounted in the model. An important feature of the sewing bands is their ability to sustain residual forces at large deformations, hence increasing the deformability of brick infill walls. Currently, it is recommended that sewing band reinforcement ratio should be kept in the range such that bed joint failure mode is the governing failure mode (i.e. strength based on crushing of the infill wall should not be exceeded). In order to further calibrate the proposed model for different failure modes and to estimate critical deformation levels, additional experiments are needed especially using various fiber types, amounts and with different boundary frame details and aspect ratios.

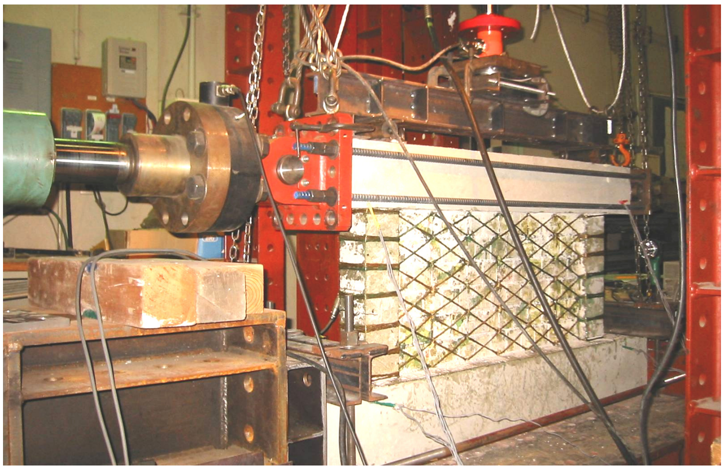


Figure 7. Experimental Setup of Cyclic Brick Infilled Frame Tests

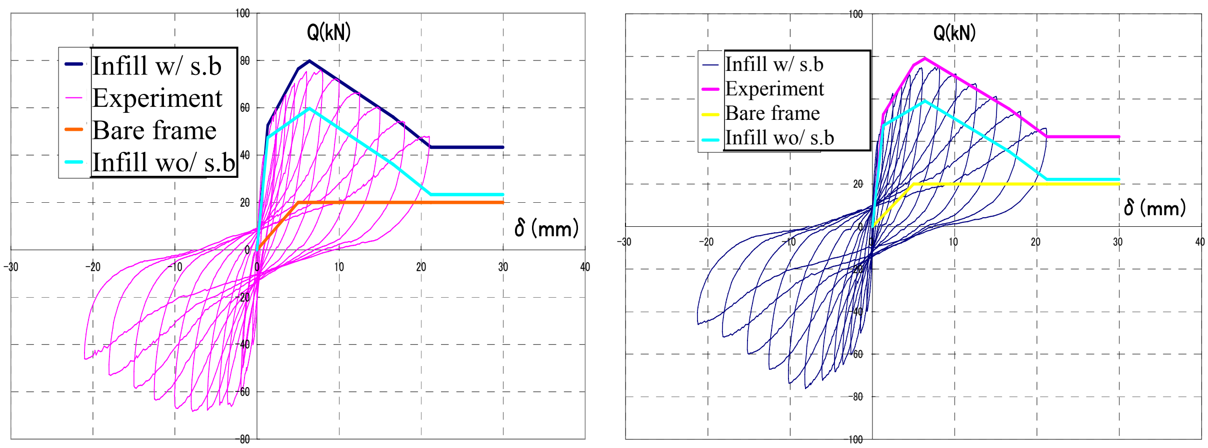


Figure 8. Comparisons of Load-Deformation Response of Test Specimens and Model Estimations

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