INELASTIC SEISMIC RESPONSE OF REINFORCED CONCRETE BUILDINGS WITH FLOOR DIAPHRAGM OPENINGS

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ABSTRACT

Floor and roof systems are designed to carry gravity loads and transfer these loads to supporting beams, columns or walls. Furthermore, they play a key role in distributing earthquake-induced loads to the lateral load resisting systems by diaphragm action. In reinforced concrete buildings, the in-plane flexibility of the floor diaphragms is often ignored for simplicity in practical design (i.e., the floor systems are frequently treated as perfectly rigid diaphragms). Past research, which is acknowledged in recent building standards, has shown that this assumption can result in considerable error when predicting seismic response of reinforced concrete buildings when diaphragm plan aspect ratio is greater than 3:1 (Kunnath, 1991 & ASCE-7, 2005). However, the influence of floor diaphragm openings (typically for the purpose of stairways, shafts, and other architectural applications) has never been considered. In order to investigate the influence of diaphragm openings on the seismic response of reinforced concrete buildings; two 3-story reinforced concrete buildings are designed as a Building Frame System according to the International Building Code (IBC, 2006). Each building is assumed to be in the Saint Louis, Missouri area and it's analyzed with and without floor openings -4 cases. The inelastic behavior of the buildings is investigated under both static lateral loads (push-over) and dynamic ground motions (time-history), where a suite of three well-known earthquakes is scaled to model moderate ground motions in the Saint Louis, Missouri region. The diaphragm parametric study conducted involves two opening size/locations and two lateral load resisting frames stiffness/locations, where three types of floor diaphragm models (rigid, elastic, and inelastic) are assumed. The result summary is presented in this paper and discussed. It was concluded that in order to capture the seismic response of reinforced concrete buildings with floor diaphragm openings accurately; it is necessary to use an inelastic diaphragm model.

KEYWORDS: Inelastic, seismic, response, concrete, diaphragm, openings

1. INTRODUCTION

Floor and roof systems play a key role in distributing lateral loads by exhibiting diaphragm-like behavior, but they are only designed to carry gravity loads and transfer these loads to supporting beams, columns or walls. Because floors systems (horizontal diaphragms) typically function as deep beams with short spans, they have very high stiffness and strength in comparison with other structural components and are often considered to be infinitely rigid in reinforced concrete buildings. Cast-in-place concrete and concrete filled metal decks are normally considered rigid diaphragms. The concept of rigid floor diaphragms for building type structures was introduced nearly 40 years ago as a means to simplify the solution process. In the case of rigid floor diaphragms, the floor plate is assumed to translate in plan and rotate about a vertical axis as a rigid body, the basic assumption being that there is no in-plane deformation in the floor plate. However, this assumption has serious limitations for buildings with considerable in-plane diaphragm deformation (Panahshahi, 1988). For diaphragms assumed to be infinitely stiff (rigid), the force distribution depends only on the relative stiffness between the vertical resisting elements. With the advances in numerical methods and computer technology, it is important in some cases that floor systems be modeled as flexible (elastic or inelastic) diaphragms (Panahshahi, 1991 & Kunnath, 1991) so that diaphragm in-plane deformations are included in the analysis. The inelastic deformations are important not only for proper evaluation of the lateral load distribution to vertical resisting frames and walls but also to determine the ductility demand of floor diaphragms and frames. In this paper all three types of diaphragms (elastic, inelastic and rigid) will be addressed in order to evaluate the effect of in-plane deformations for reinforced concrete floors with and without openings on the seismic performance of buildings with frames and shear walls. The inelastic dynamic response of the buildings will be evaluated by means of an enhanced computer program IDARC2 (Panahshahi, 1988) via a suite of earthquakes as the ground motion input. The program uses macro-modeling schemes to account for diaphragm in-plane deformations due to shear and flexure while taking into account stiffness deterioration and strength degradation of the reinforced concrete beams, columns, shear walls and slabs due to inelastic cyclic loadings caused by ground motion.

2. RESEARCH SIGNIFICANCE

Although numerous publications dealt with the behavior and design of diaphragms, it is clear that there are several issues that have not been resolved yet. Openings in diaphragms are often unavoidable and their presence can significantly modify the behavior of the diaphragm. At present, the designer assumes that the reinforced concrete floor diaphragm is rigid when diaphragm aspect ratio is less than 3:1 (ASCE 7, 2005) or is elastic when the aspect ratio is greater than 3:1. These assumptions may lead to erroneous results particularly in reinforced concrete buildings with floor openings. This issue is considered important, as it is the least understood subject in this area, since there is no quantification of the error in diaphragm ductility demand and frame shear forces as a result of ignoring openings. Therefore, in this study, inelastic diaphragm deformations are incorporated in the analysis in order to capture the “real” behavior of the structural members as opposed to the “assumed” one in low-rise rectangular buildings. The latter will yield a better understanding of the structural behavior and hence design of reinforced concrete buildings with floor diaphragm openings when subjected to strong ground motion.

3. OBJECTIVE

The main goal of this research project is to gain in-depth understanding of the seismic response of low-rise rectangular reinforced concrete buildings with floor diaphragm openings. This is achieved by investigating the applicability of rigid, elastic and inelastic floor assumptions to floor diaphragm models with aspect ratio of 4:1 when openings are present. Floor openings of various sizes are placed in symmetric and asymmetric plan locations in order to investigate the influence of floor diaphragm flexibility on the distribution of lateral loads to frames and shear walls. By capturing the true behavior of reinforced concrete buildings with diaphragm openings, the results of this study will lead to valuable information.

4. DESCRIPTION OF STRUCTURES AND SEISMIC DESIGN PARAMETERS

In the present study, two 3-story, 39 ft high (i.e., 13 ft story height) reinforced concrete buildings are investigated. The structure’s plan is twelve 20 ft bays in length (240 ft total) and three 20 ft bays in depth (60 ft total), with 8 in. thick shear walls placed symmetrically either at the end frame (with non-symmetric floor openings) or placed at two intermediate frames (with symmetric floor openings) as shown in Figures 1, 2, 3, and 4. The columns are 14 in. x 14 in. and the girders are 14 in. x 24 in. Floor diaphragm is a one-way 5 in. slab spanning across the frames with intermediate 14 in. x 14 in. supporting beams, i.e., 10 ft span. All elements were designed and detailed to meet ACI 318-05 and IBC 2006 prescribed forces. The lateral force resisting system in the N-S direction (short direction) consists of “Building Frame System” in which the shear walls will resist the entire seismic load, and intermediate moment resisting frames (IMRF) are used in the E-W direction (long direction). The equivalent lateral forces generated were based on a site class C, seismic design category (SDC) C and seismic use group I.

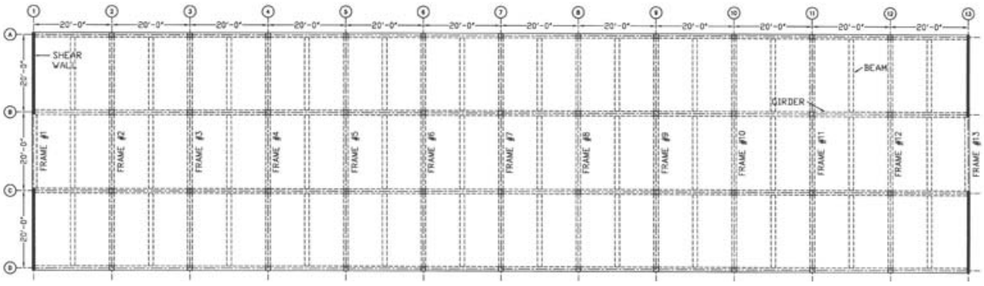

Figure 1 Solid diaphragm plan with end walls (Case 1)

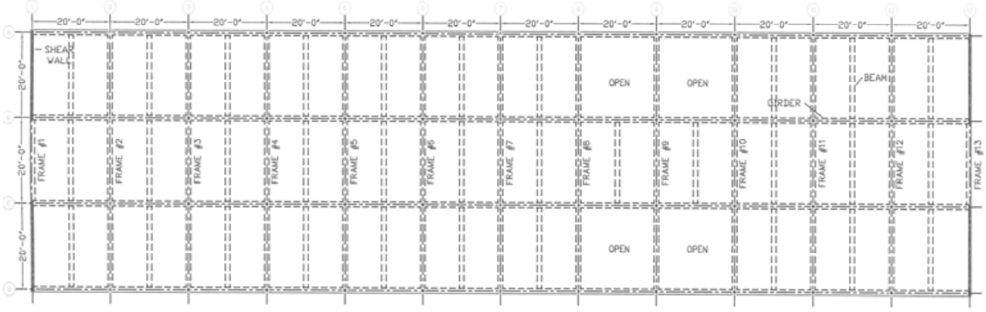

Figure 2 Open diaphragm plan with end walls (Case 2)

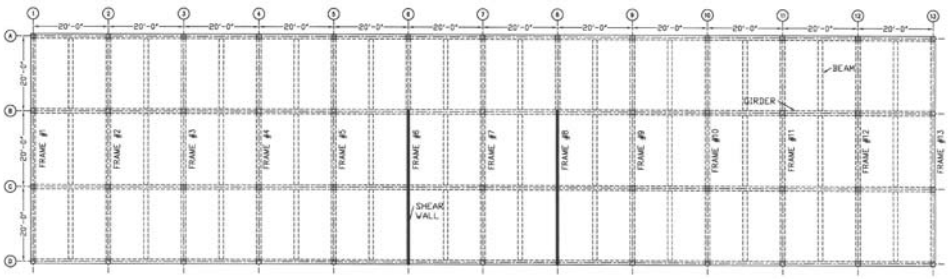

Figure 3 Solid diaphragm plan with intermediate walls (Case 3)

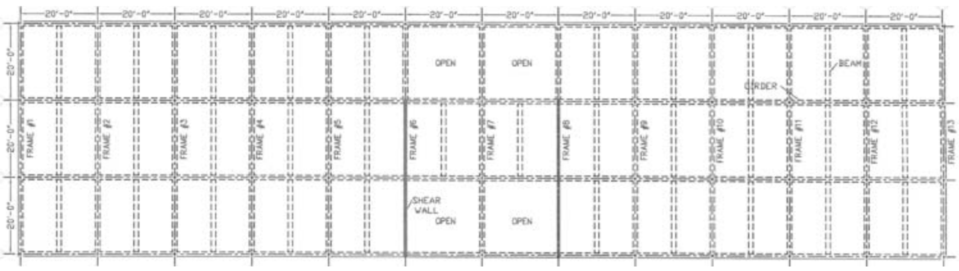

Figure 4 Open diaphragm plan with intermediate shear walls (Case 4)

All buildings were assumed to be in Saint Louis, Missouri, and hence are designed and detailed accordingly with the seismic parameters shown in Table 1. All elements were designed using concrete compressive strength of 4000 psi and grade 60 reinforcing steel with an applied uniform live load of 50 psf and super imposed dead load of 20 psf. Members' structural reinforcing details are given in Table 2.

Table 1 Seismic parameters per IBC 2006

Parameter	Value
Short Period Acceleration, S_s	0.57
Long Period Acceleration, S_l	0.19
Short Period Site Coefficient, Fa	1.17
Long Period Site Coefficient, Fv	1.59
Short Period Spectral Response Acceleration Parameter, S_{DS}	0.45
Long Period Spectral Response Acceleration Parameter, S_{Dl}	0.20
Response Modification Factor, $R_{N\text{-}S}$ & $R_{E\text{-}W}$	5.00
Over-strength Factor, $\Omega_{o,\ N\text{-}S}$ & $\Omega_{o,\ E\text{-}W}$	2.50
Deflection Amplification Factor, $C_{d,\ N\text{-}S}$ & $C_{d,\ E\text{-}W}$	4.50
Fundamental Period of Structure, $T_{a,\ N\text{-}S}$	0.31 sec.
Fundamental Period of Structure, $T_{a,\ E\text{-}W}$	0.43 sec.
Base Shear Seismic Coefficient, Cs	8.9 %

Table 2 Reinforced concrete elements details per ACI 318-05

Element Type	Element Size	Steel Reinforcing
Slab	5 in.	#3 @ 12 in. one-way
Columns	14 in. x 14 in.	8-#6 verticals w/#3 @ 6 in. ties
Walls	8 in.	#6 @ 12 in. each way vertical & horizontal
Girders	14 in. x 24 in	5-#6 top & bottom w/#3 @ 10 in. stirrups
Beams	14 in. x 14 in.	6-#5 top & bottom w/#3 @ 6 in. stirrups

5. ANALYTICAL MODELING

IDARC2 is a computer program for two-dimensional analysis of 3D building systems in which a set of frames parallel to the loading direction is interconnected by transverse elements to permit flexural-torsional coupling. The details of the analytical schemes may be found in Panahshahi, et al. (1988). In IDARC2, a reinforced concrete building is idealized as a series of plane frames linked together by floor slabs and transverse beams. Each frame must lie in the same vertical plane. Consequently, a building is modeled using the following element types: floor slabs, beam-columns, shear walls, shear wall edge columns, and transverse beams. All components of the building, except transverse beams, are modeled as tri-linear, inelastic elements with concentrated plasticity at member ends with a distributed flexibility rule to account for the spread of plasticity. A linear variation of flexibility is assumed in deriving the flexibility matrix.

A typical floor slab is modeled using two degrees of freedom (DOF) per node: one lateral and one rotational. Two inelastic springs are used to model shear and flexure independently. Also, main beam-column elements form a vertical plane in the direction of earthquake loading. They are modeled as continuous inelastic shear-flexure springs in which shear-deformation effects have been coupled by an equivalent spring. The modeling of shear wall elements is similar to that for floor slabs except for the inclusion of axial effects and the incorporation of edge columns at the ends of the wall. Walls may, however, be modeled with or without edge columns. To incorporate the effects of transverse elements to account for their restraining action due to the axial movements of vertical elements, especially edge columns in shear walls, and permit flexural-torsional coupling with the main elements, each transverse T-beam is modeled using elastic springs with one vertical and one rotational DOF. As for the nonlinear dynamic analysis; IDARC2 follows the Newmark-Beta algorithm for the step-by-step solution of the dynamic equation of motion. The hysteretic model used for the analysis incorporates three parameters in conjunction with a nonsymmetric trilinear curve to establish the rules under which inelastic loading reversals take place. The stiffness degradation factor α specifies the degree of reduction in the unloading stiffness and the reduction in area enclosed by the hysteresis loops for consecutive loading cycles. The strength deterioration factor β is the ratio computed as the amount of incremental damage caused by the increase of the maximum response divided by the normalized incremental hysteresis energy. The pinching factor γ reduces the stiffness of the reloading paths as well as the area of the hysteresis loops and the amount of dissipated energy. These hysteretic parameters can be combined in various ways to achieve a range of hysteresis behavior patterns typical to reinforced concrete sections. Details of significance and the general effects of these parameters can be found in Panahshahi, et al. (1988).

As mentioned earlier, IDARC2 is used to conduct inelastic static (push-over) and dynamic (time-history) analyses for the four reinforced concrete buildings addressed in this study. All three different diaphragm types (elastic, inelastic and rigid) will be investigated for every case. Each of the two buildings will have a solid diaphragm and a diaphragm with openings (4 cases). As for the openings, two different size/location floor openings are selected (as shown in Figures 1 through 4).

Since there are no available records of any severe earthquakes for the Saint Louis area, a suite of three well-known earthquakes is chosen with periods close to that of the buildings in question. This preference was made to maximize any resonance that may take place during an earthquake. Since the peak ground acceleration (PGA) recorded is higher than that of the site at 0.27g, the seismic input for the dynamic analysis was scaled accordingly, as shown in Table 3.

Table 3 Earthquakes characteristics used in IDARC2 analysis

Earthquake	**PGA, g**	**T_g, sec.**	**Scale**
Loma Prieta - Corralitos - 1989	0.41	0.34 sec.	0.659
San Fernando - Pacoima Dam -1971	1.15	0.40 sec.	0.235
Parkfield - Cholane -1966	0.48	0.40 sec.	0.563

6. RESULTS

For all the four buildings considered, the investigation proceeds by the pushover analysis (inelastic static) and then is completed with the inelastic dynamic analysis. From the pushover analysis, it is observed that in buildings with solid diaphragms, the slab elements yielded prior to the wall elements while the opposite is observed in buildings with open diaphragms. For example, the failure sequence for Cases 1 and 2 is compared in Figures 5 and 6, respectively, where typical structure base shear coefficient vs. frame drift is plotted.

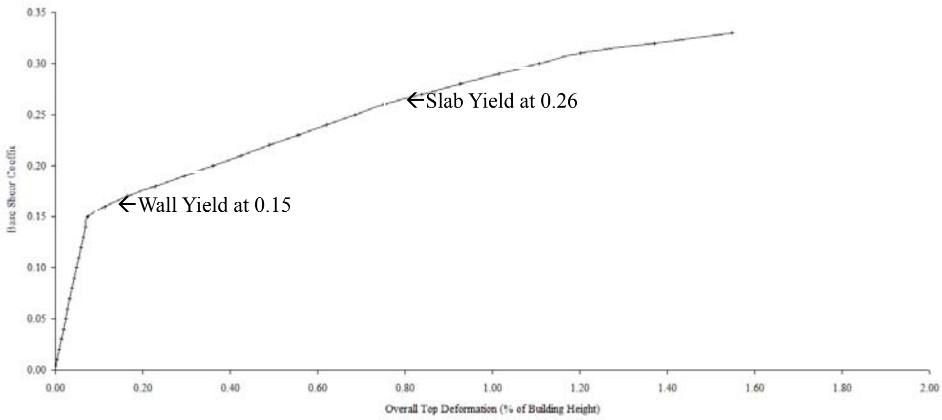

Figure 5 Solid diaphragm base shear vs. Frame 7 overall top deformation -% of building height- (Case 1)

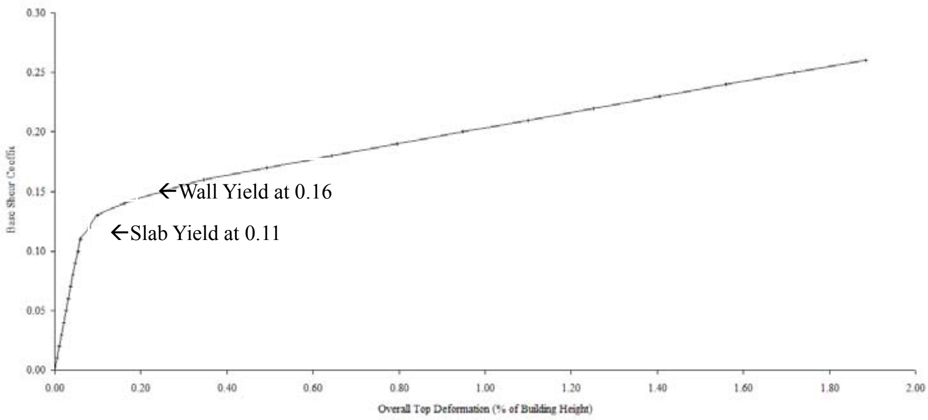

Figure 6 Open diaphragm base shear vs. Frame 8 overall top deformation -% of building height- (Case 2)

Typical plot of the normalized floor displacements obtained from dynamic analysis for rigid, elastic, and inelastic slab models are compared in Figure 7 and 8 for Case 1 and Case 2, respectively, for the most critical scenario among the three earthquakes used.

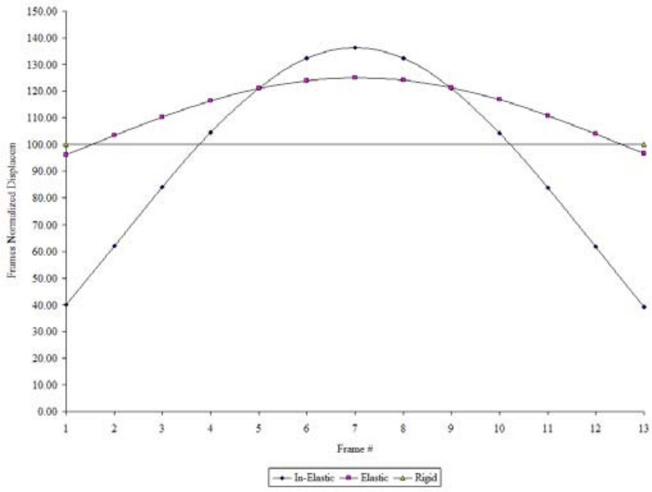

Figure 7 Loma Prieta-Solid Diaphragm top story normalized frames displacements (Case 1)

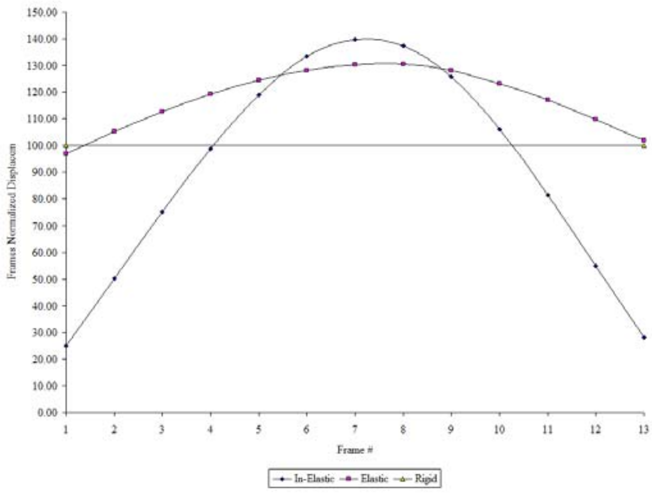

Figure 8 Loma Prieta-Open Diaphragm top story normalized frames displacements (Case 2)

It is observed that significant in-plane deformations occur in diaphragms with openings due to yielding of floor slab, which in turn subjects the supporting beam-column frame to an increased frame shear.

The summary of the dynamic analysis results for all the cases subjected to the Loma Prieta earthquake, where the maximum floor deformations were observed, is given in Table 4. Examination of the maximum in-plane diaphragm deflection (which occurred at the third level) indicates that the results obtained using the in-elastic slab model are 2.95 - 4.0 times greater than the values obtained by using elastic slab model. Consequently, the frame shear redistribution due to inelastic slab deformations increased the frame shear in Cases 2 and 4. For example, the percentage of base shear load absorbed by frames can be as high as 30.6% (1.86 and 1.28 times the values obtained from rigid and elastic diaphragm assumptions respectively) of the lateral load applied (Case 2). Thus, using elastic (or rigid) diaphragm assumption in evaluation of seismic response of the RC buildings with diaphragm openings results in a non-conservative estimation of the floor deformations and frame shears.

Table 4 Results summary of dynamic analysis using Loma Prieta earthquake

Loma Prieta Earthquake												
Output	Case 1			Case 2			Case 3			Case 4		
	Solid Diaphragm			Open Diaphragm			Solid Diaphragm			Open Diaphragm		
	Inelastic	Elastic	Rigid	Inelastic	Elastic	Rigid	Inelastic	Elastic	Rigid	Inelastic	Elastic	Rigid
Diaph. Max. Inplane Defl., in.	0.968	0.319	0.000	1.244	0.310	0.000	0.817	0.277	0.000	1.384	0.423	0.000
Base Shear, V kips	1373.10	1397.80	1523.90	1010.10	1376.70	1496.30	1727.60	1885.60	1919.50	1216.90	1926.40	1878.90
%V to Walls	75.03	75.53	80.85	69.38	76.08	83.59	84.83	87.39	96.58	80.00	85.31	96.82
%V to Frames	24.97	24.47	19.15	30.62	23.92	16.41	15.17	12.61	3.42	20.00	14.69	3.18
Period, T sec.	0.307	0.307	0.263	0.315	0.315	0.260	0.202	0.202	0.170	0.219	0.219	0.170
Bldg. Max. Top Displ., in.	1.317	1.239	0.996	1.293	1.236	0.961	0.785	0.491	0.455	1.309	0.618	0.352

7. CONCLUSION

There is a significant void in published literature on the subject of inelastic seismic response of reinforced concrete buildings with diaphragm openings. The investigation of inelastic seismic response of two 3-story reinforced concrete buildings with diaphragm aspect ratio of 4:1 with symmetric and non-symmetric floor plan openings shows that ignoring inelastic diaphragm deformations, i.e. as in rigid and elastic diaphragm assumptions, done in current design practices will result in an incorrect assessment for the nonlinear seismic response of such buildings. Hence, the influence floor openings cannot be overlooked in such buildings.

All case investigated in this study gave insight into the influence of diaphragm rigidity assumptions (inelastic, elastic and rigid) on nonlinear seismic response of the buildings. Further studies are currently under way to obtain practical design guidelines for improvement of seismic codes incorporating the effects of flexible floor diaphragms with openings.

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