CURRENT RESEARCH AT LEHIGH UNIVERSITY ON
CONCRETE FLOOR SYSTEMS UNDER IN-PLANE SEISMIC LOADING

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SUMMARY

A comprehensive investigation is underway on the contribution of floor systems to the earthquake resistance of steel and concrete building structures. Two concrete floor systems have been experimentally studied in detail, the flat plate system and the slab-on-beam system. Elastic and ultimate behavior of slab panels were determined for a variety of in-plane loading, shear span aspect ratio and combination with out-of-plane loading. The effectiveness of epoxy-injection repair of damaged slab was also examined. This report describes the project in general, and gives some preliminary observations from these tests.

INTRODUCTION

A comprehensive research program is being conducted at Lehigh University to study the structural behavior of building floor systems under in-plane loads. This investigation is aimed at providing information to enable a complete analysis of building structural systems subjected to dynamic seismic loading. The seismic resistance of a building frame is primarily provided by specially designed systems in vertical planes, such as shear walls and rigid or braced frames. However, the floor systems also play a very important role. In the direction of the applied lateral load, they combine with vertical members to form structural frames. In addition, they form the horizontal diaphragms between parallel vertical seismic-resisting systems, transmitting and distributing the lateral forces in the transverse direction. Their in-plane characteristics are necessary in order to make a complete analysis of the entire structure as a three-dimensional system.

The scope of this research includes analytical and experimental studies of several floor systems which are commonly used in buildings with either steel or reinforced concrete structural frames. To date, two

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concrete floor systems have been tested in detail. The testing of the flat plate system is reported elsewhere at this conference. This report deals with general information on the research project, as well as preliminary test results of the second floor system, that of two-way slab supported on edge beams. Floor systems yet to be studied include metal deck and waffle slab.

The ultimate goal of this research is to develop design recommendations for building structural systems taking into consideration the contribution of floor systems to the seismic resistance. For the experimental work, the primary objective is to determine the fundamental in-plane characteristics of the various floor systems, including their stiffness, strength and displacement capacity in both the elastic and the post-elastic ranges. Parameters included in the experimental study are: (1) Nature of in-plane loading, monotonic or cyclic, (2) shear span aspect ratio, or moment-to-shear ratio, (3) influence of gravity (out-of-plane) loading, (4) effectiveness of epoxy-injection repair of damaged floor, and (5) interaction of supporting columns.

TEST SPECIMENS

The test specimens for both floor systems were based on the same prototype structure, which had columns spaced 24 ft. center-to-center on a rectangular grid and floors spaced at 12 ft. center-to-center. The structural design of the floor slabs was made in accordance with the current ACI Building Code (ACI 318-77) for a service live load of 80 psf. The material strengths adopted for the design were: 4000 psi for concrete in the system (including the supporting beams), 5000 psi for concrete in vertical members (including columns and shear walls), and 60000 psi for reinforcing bars. A scale ratio of 4.5 to 1 was used to arrive at the gross dimensions of the test specimens. Reinforcement of the specimens was calculated directly using the reduced dimensions.

Each of the test specimens contained three consecutive floor panels supported on two shear walls and four columns, as shown in Fig. 1. Extensions beyond the column center lines, equal to one-quarter of panel dimension, were provided in all directions to represent the adjacent slab panels and also to provide for anchorages of reinforcing bars. As shown in Fig. 1, the specimen panel dimensions were 64 in. by 64 in., and the overall dimensions of the three-panel assemblage were 96 in. by 224 in. The specimen columns were 5.34 in. square, corresponding to 24 in. square columns for the prototype. The shear wall thickness was made also 5.34 in., so that each of the three panels would have the same clear dimensions. The height of the columns and shear walls in the specimens was 16 in. to the center plane of the floor slab. This height was selected to reflect points of inflection at mid-height of the vertical members, as well as identical vertical members above and below the tested floor.

The slab thickness for the flat plate specimens was 2.22 in., corresponding to 10 in. thickness for the prototype. For the slab-on-beam specimens, the slab thickness was 1.55 in., with edge beams 2.67 in. wide and projecting 3.77 in. below the slab. The corresponding dimensions for the prototype were 7 in., 12 in., and 17 in., respectively.

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On account of the small dimensions of the specimens, special atten-
tion was given to the concrete particle size and the reinforcing bars.
The aggregate size was restricted to 1/4 in. maximum, and special deformed
wires of sizes D2, D2.5, D3 and D5 (having cross-sectional areas of
0.02, 0.025, 0.03 and 0.05 sq. in., respectively) were used for slab and
beam reinforcement. All slab panels were reinforced as typical interior
panels. It should be pointed out that much of the slab reinforcement was
controlled by the temperature and shrinkage requirements and exceeded
significantly the amount required to carry the design load.

Each column in the specimen contained four vertical bars of #3 size,
with D2 size closed ties. Reinforcement of the shear walls was not
designed according to the adopted design load, but made extra heavy, in
order to assure that the ultimate strength of the floor system would be
reached in all tests.

Two identical three-panel specimens were fabricated and tested for
each floor system studied.

TEST SETUP

A group of special test setups was developed to perform these tests.
Four heavily reinforced concrete pedestals were erected on the laboratory
floor. These serve as supports of the floor system specimen, and provide
access to the underside of the specimen. The top of each pedestal is
designed to receive either a shear wall, or a pair of columns. In either
case, a variety of degree of fixation is possible. With the help of a
set of heavy steel braces, the shear wall can be fixed against any motion
in the plane of the floor. In this condition, the slab panels on the two
sides of the shear wall are effectively separated from each other. No
force is transmitted, thus enabling the testing of each panel separately.
Alternately, the shear wall may be restrained from translation only, per-
mitting rotation about a vertical axis (Fig. 2). Finally, the wall can
also be completely released and become free to slide about on top of the
pedestal (Fig. 3). The column support fixtures are also adjustable to
provide either a free sliding or a fixed base condition. In the free
sliding condition, the column stubs provide no resistance to the applied
lateral load. In the fixed mode, the columns are restrained to rotate
about the fixture hinge, located at 16 in. below the slab center plane.

The in-plane loading was applied by a double-acting jack along the
column line. A specially designed steel frame was used to distribute the
load uniformly to five studs embedded on the column centerline and spaced
evenly at 21.3 in. on centers. Such a five-point distribution of the
applied load was used to simulate a shear action, and to prevent local dis-
tress under a heavy point load.

The out-of-plane loading was applied as a series of concentrated
loads located at the center of each ninth portion of the slab panel. All
point loads within the panel width were controlled by one gravity load
simulator, and the loads were distributed evenly through a series of
levers. The gravity load simulator was so designed that significant dis-
placement of the specimen was permitted in the direction of the in-plane

loading without affecting the direction, nor the magnitude of the applied gravity load.

Electric resistance strain gages were used on reinforcing bars, as well as on the surface of concrete for strain measurements. In several locations, the strain gages were arranged in rosettes, so that the principal strain directions could be determined. In-plane movements of the test panel were measured by a number of LVDT's, arranged to detect all deformations of the test panel, as well as displacements of the supports. For specimens subjected to gravity loads, vertical displacements at several strategic points were measured by a precision level. Dial gages were used to supplement the LVDT and level readings at several places. At testing time, the application of load was controlled through a recording oscilloscope and digital readout equipment. An automatic data-acquisition system was used to record the readings from the LVDT's and the strain gages.

TESTING PROCEDURES

Each three-panel specimen was initially tested for its free vibration frequencies, both in-plane and out-of-plane. Vibration was excited by either a hammer impact or the sudden release of an applied load. The vibration of the specimen was detected by an accelerometer and recorded on an oscilloscope. By using successively narrower filtering frequency bands, it was possible to determine the dominant natural frequency. This test was repeated several times during the course of the test, in order to determine the cumulative deterioration of the specimen.

After the initial free vibration tests, the three-panel specimen was tested in its entirety for the elastic stiffness characteristics of the slab panels. For this test, the shear walls were supported in the free-to-rotate mode, and the columns were free to slide about (Fig. 2). Small in-plane loads, were applied along the column lines, first symmetrically, then antisymmetrically. In this condition, the specimen resembled a simply-supported overhanging beam for the applied loads. The measured displacements and rotations from these tests can be analyzed to yield a set of stiffness coefficients for the basic test panel (64 in. by 96 in.). In addition, the fundamental bending and shear rigidity values of the test panel can also be determined. The loadings for these tests were kept low to insure elastic behavior.

Following the initial vibration and stiffness tests, the slab panels were tested, each separately, for complete behavior under in-plane loading, including both elastic and post-elastic ranges. The six slab panels were tested under a variety of loading arrangements as indicated in Table 1.

For these ultimate load tests, the shear wall supporting the slab panel being tested was fixed to the pedestal, all other vertical elements were placed in the free mode. The test panel then resembled a cantilever beam (Fig. 3). Application of in-plane loading was controlled by the total displacement at the "free" edge of the test panel. In the monotonic tests, displacement was increased continuously until failure was obtained (by decreasing resistance, excessive cracking, and rupture of reinforcing bars). The direction of in-plane load was then reversed, and continued

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until failure was reached in the opposite direction. In cyclic load tests, repeated and reversed displacements of increasing magnitude were applied, three complete cycles at each amplitude, until failure occurred.

With regard to the gravity load application, the difference in dead load effects in the specimen and the prototype structure should be noted. Because of the reduced scale, the self-weight effect of the specimen was only 22% of that in the prototype. For four of the test panels, no compensation was made for this difference. The applied gravity load for panels II1 and II2 raised the total out-of-plane load to the full service level (dead plus live) used in the design.

After the ultimate load tests, panels I1, I2, II1, II2 were repaired by the epoxy injection method, and were tested again, each under the same loading arrangment as previously. These same panels were then repaired again and retested, this time with the column bases fixed, in order to study the effect of column interaction.

A sequential order of the above described tests was selected to minimize the need for moving the loading and supporting fixtures, rearranging the LVDT's, and reconnecting the data-acquisition system.

TEST RESULTS

Results of the initial stiffness tests for the two floor systems tested are summarized in Table 2. The displacements for the slab-on-beam system are about 20% larger than the corresponding values for the flat plate specimen. This differential is approximately in the same ratio as the slab thicknesses. The edge beams apparently have little influence on the in-plane elastic stiffness of the floor system. These results also agree quite well with calculated values based on finite element analysis or deep beam theory when shear deformations are included.

Table 3 shows the in-plane vibration frequency of the slab-on-beam specimens measured at various times during the course of testing. To minimize setup handling time through the ultimate load tests, the in-plane load distribution frame was left attached to the specimen for the intermediate free vibration tests. The initial vlaue with loading frame attached was used as a basis for comparison. The scatter of this frequency for the several panels was believed to be caused by differences in the assemblage. After epoxy-injection repair, the natural frequency was found to be 75 to 80% of the original value, reflecting a stiffness ratio of approximately 60%. The stiffness after a load test depends strongly on the state of cracks at that time. Since some cracks opened during the first half cycle of loading and would be in the process of being closed during the second half cycle, the true state of cracking was rather ambiguous, and too much significance must not be attached to the numerical values. Nevertheless, it is clear that the slab stiffness is seriously reduced at the end of each test.

The results of the series of ultimate load tests of the slab-on-beam specimens are summarized in Table 4. In most monotonic tests, a sizable difference exists between the maximum loads for the two directions. It is

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reasonable that the extent of damage caused by the failure in the first direction would affect the specimen strength in subsequent tests, in the opposite direction. In cyclic load tests, each half cycle of loading caused only a small amount of additional damage, hence the test results are more symmetrical. Observations can be made on the significance of the experimental parameters from the results in Table 4. Cyclic loads cause the in-plane strength to decrease by nearly 20%. The presence of gravity load causes a decrease of about the same magnitude. Panel 3, with a large shear span, shows significantly less in-plane shear capacity, the reduction ratio being more than 50%. Epoxy-injection appears to be very effective in restoring the panel strength, although the displacement capacity is not recovered. This is in agreement with the previous observation that the repaired specimens were less stiff than the original. The cyclic load also resulted in reduced maximum displacement. In all tests, including both floor systems, the primary crack directly causing failure of the slab panel lay nearly parallel to the fixed shear wall, at a location approximately one-fourth panel length (16 in.) from the wall (Fig. 3). It is noted that many of the top reinforcing bars perpendicular to the shear wall are terminated at this location. There is a sudden reduction of moment capacity against bending caused by the in-plane loading. The moment strength calculated for this section, using bending theory, agreed reasonably well with the test results.

One difference in the cracking behavior of the two floor systems is worth noting. In the flat plate specimens, all cracks originated at the tensile edge of the slab, and progressed inward as load increased. In the slab-on-beam specimens, many cracks started at the bottom of the beam running perpendicular to the shear wall, and developed in both directions. The beams also appear to have a constraining effect on the crack width, and the slab panels were able to maintain a nearly constant resistance while continuing to deform. The final failures were triggered by rupture of beam-reinforcing bars. A few cracks were seen to run in a diagonal direction. They all originated at the beam directly in line of applied load, and at locations of the embedded studs transmitting in-plane load. They are believed to be the results of local bearing distresses.

Comparing the in-plane load strengths of the two floor systems, the slab-on-beam system is approximately 20% weaker. This ratio is almost identical to the ratio of the slab thicknesses of the two systems (1.77 in. vs. 2.22 in.), it is apparent that the supporting beams do not contribute significantly to the in-plane strength.

PRELIMINARY CONCLUSIONS

Analysis of test results are in progress at the time of this writing. In the following are listed several preliminary conclusions:

1. The in-plane load strength of the slab panels can be estimated by the moment strength at the quarter panel section.

2. The supporting beams in the slab-on-beam system contribute little towards the in-plane strength of the floor panel. They form a restraining boundary frame, and improve the displacement capacity (ductility).

3. Cyclic loading causes the in-plane strength to decrease by approximately 20%. The displacement capacity also decreases by a similar percentage.

4. The presence of full service gravity load reduced the in-plane strength of the floor panel by nearly 20%. However, the displacement capacity is not seriously affected.

5. Shear span aspect ratio is an important factor controlling the in-plane strength. The increase of shear span from 64 in. to 128 in. reduced the in-plane strength by more than 50%.

6. Epoxy-injection repair is very effective in restoring the in-plane strength of the floor panel. However, neither the stiffness nor the displacement is restored.

7. The elastic in-plane stiffness of the floor panel can be reasonably estimated by the deep beam theory, including shear deformations, or by the finite element analysis.

ACKNOWLEDGMENT

TABLE 1

LOADING ARRANGEMENTS

Specimen	FI, BI			FII, BII		
Panel	I1	I2	I3	II1	II2	II3
Nature of Loading						
Monotonic	X		X	X		
Cyclic		X			X	X
Gravity Load						
No	X	X	X			X
Yes				X	X	
Shear Span (in.)						
64	X	X		X	X	
128			X			X

TABLE 2

SUMMARY OF INITIAL STIFFNESS TESTS

Specimen	FI	BI	BII
Symmetrical Test			
Deflection δ	835×10^{-6} in./kip	1080	1100
Total Rotation θ_m	7.6×10^{-6} rad/kip	10.4	--
Anti-Symmetrical Test			
Deflection δ	1640×10^{-6} in./kip	2140	1920

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TABLE 3

IN-PLANE FREE VIBRATION FREQUENCIES

Specimen	BI		BII	
Panel	1	2	1	2
Initial				
Bare	140 Hz	97 Hz	146 Hz	120 Hz
With Loading Frame	123	90	109	98
After First Test	31	48	37	---
After Repair	92	85	88	---
After Second Test	57	51	34	---

TABLE 4

STRENGTH TEST RESULTS OF SLAB-ON-BEAM SPECIMENS

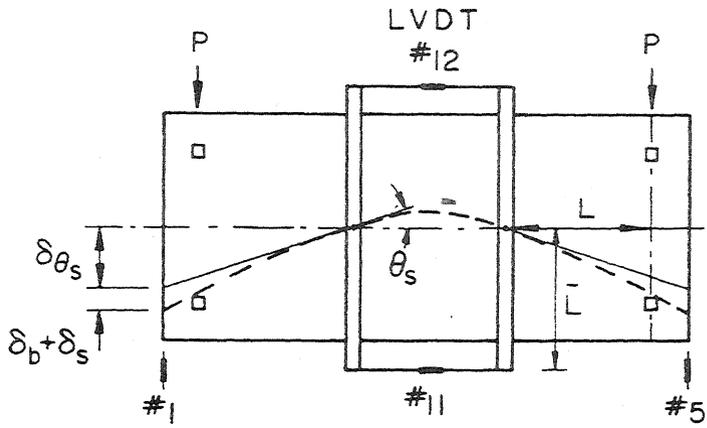| Test Panel		Maximum Load (kip)		Maximum Displacement (in.)	
I1	Virgin	27.0	−19.9	0.334	−0.293
	Repaired	28.6	−21.0	0.245	−0.324
I2	Virgin	21.3	−21.7	0.198	−0.190
	Repaired	17.3	−18.5	0.116	−0.125
II1	Virgin	23.0	−20.2	0.363	−0.363
	Repaired	25.8	−19.5	0.351	−0.245
II2	Virgin	19.1	−18.7	0.247	−0.267
	Repaired	21.7	−21.3	0.238	−0.221
I3		12.8	−8.7	0.288	−0.243
II3		9.4	−9.1	0.221	−0.231

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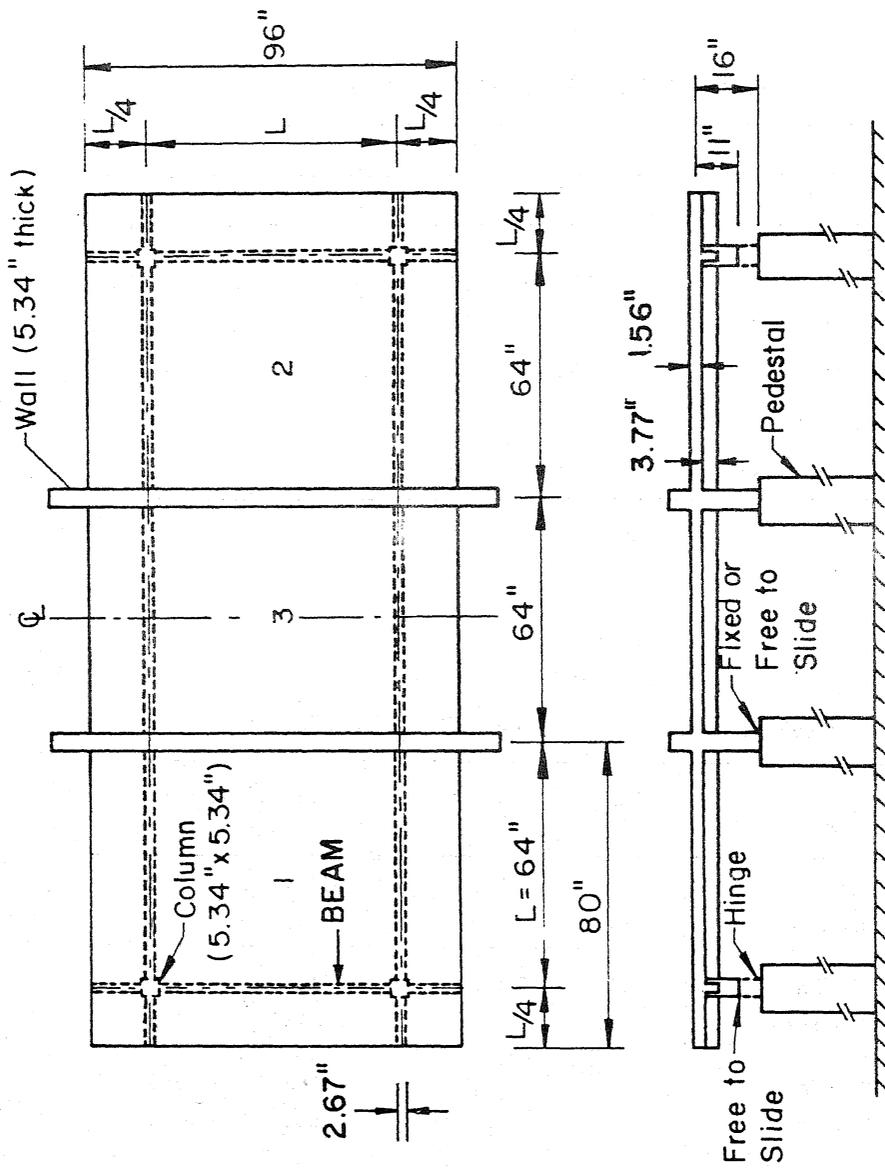
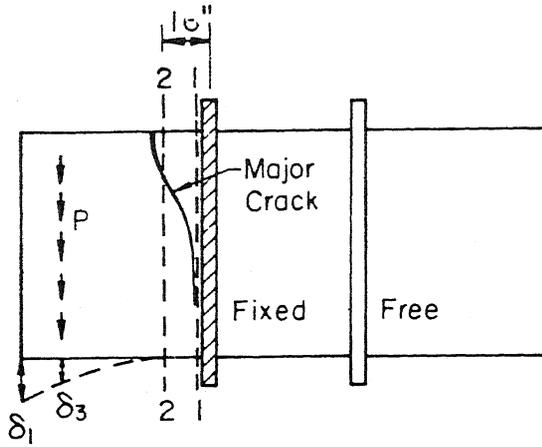Fig. 1 Specimen for Slab-on-Beam Floor System
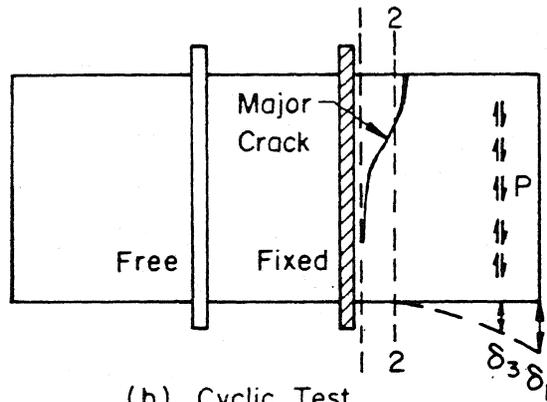
(a) Symmetrical Loading
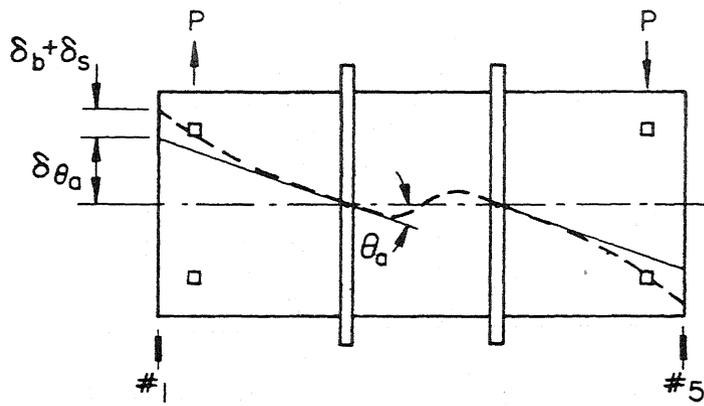
(b) Anti-symmetrical Loading

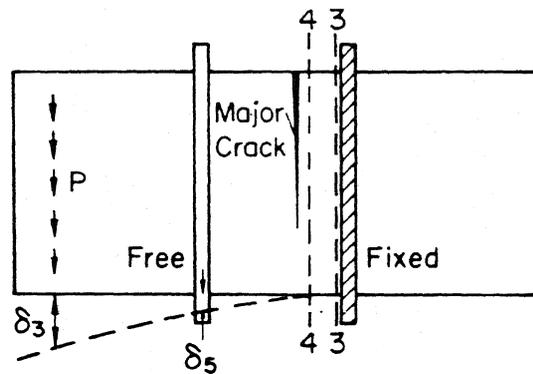Walls Allowed to Rotate, Columns Free to Slide

Fig. 2   Elastic Stiffness Tests

Columns Free to Slide

(a) Monotonic Test

(b) Cyclic Test

Monotonic: F-1, Cyclic: F-2

(c) Monotonic and Cyclic
Tests of Panel 3

Fig. 3 Ultimate Load Tests of Individual Floor Panels

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