Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VI)

9-1-9

FEASIBILITY STUDIES ON AN ADVANCED MIXED STRUCTURE

Takashi HASEGAWA[1] , Hiroyuki YAMANOUCHI[2] , Isao NISHIYAMA[3]
Takuma MAEDA[4] , Yukio IZAKI[5] , and Yasunaga FUKUCHI[6]

1. Research Assistant, Structural Dynamics Division, Dept. of Structure, Building Research Institute, Ministry of Construction, Tsukuba, Japan
2. Head of Structural Dynamics Division, BRI
3. Senior Research Engineer, IISEE, BRI
4. Senior Structural Engineer, Sato Kogyo Co., LTD., Tokyo,Japan
5. Research Engineer, Sato Kogyo Co., LTD., Atugi, Japan
6. Professor, Dept. of Architecture, Nagoya Institute of Technology, Nagoya, Japan

SUMMARY

An advanced mixed structure system consisting of columns with reinforced concrete and girders with steel was proposed in this paper with discussions verifying the structural performance and usability of this system. About the structural usability, a design simulation study was conducted on three story buildings independently designed as just steel, just reinforced concrete and mixed systems. The comparison among the three structural systems showed quantitatively the advantages of the mixed system. Concerning the structural performance, lots of seismic capacity of this novel system was confirmed through dynamic response analyses with a hysteresis model based on our experiments on girder-to-column subassemblages.

INTRODUCTION

Steel structures, in general, can provide wide free space thanks to high strength per unit weight of steel. Moreover, they have high reliability against seismic forces owing to large ductility of them. On the other hand, reinforced concrete system is cheaper in the total cost than steel, since it uses mainly cement and ground materials of low cost. Furthermore, it has a good point for living in owing to its high stiffness against lateral drift.

An advanced mixed system introduced in this paper, which comprises of reinforced concrete columns and structural steel girders, can be a prospective system combining and utilizing both the advantages of steel and reinforced concrete. In fact, some mixed systems have been used recently in low seismic zones; the Bank of China (Ref.1) is a typical example. In high seismic zones, however, they are not yet prevailing, because enough strength and energy dissipation capacity to resist earthquakes have not yet been confirmed, in particular in structural members which connect steel and reinforced concrete.

In this paper, discussed are the feasibility of the mixed system in connection with the structural performance and usability. With regard to the structural usability, design simulations were carried out on prototype, 3x3 bay, three story buildings which were designed independently with just steel, just reinforced concrete and mixed systems. The characteristics of the designed buildings were compared each other. On the other hand, the structural performance was investigated through the dynamic response analyses with a hysteresis model based on the experiments on girder-to-column subassemblages.

STRUCTURAL USABILITY

Procedure Firstly, model buildings were designed as the mixed system as well as usual reinforced concrete and steel systems. Secondly, the characteristics of the designed buildings were compared each other on the following items: 1) span length and column dimensions; 2) story stiffness; 3) story height and weight of the buildings; and 4) construction cost.

Profiles of Designed Buildings The prototype model building was a 3x3 bay, three story moment-resisting frame building with 6mx8m plan grids as shown in Fig.1. To estimate the effect of span length, the span length in the longitudinal direction of the prototype, 8m, was changed to 10m, 12m and 14m with the constant transverse span length, 6m. The height of the story was a constant value of 2.9m, which is defined as clear height between the top of the floor slab and the ceiling.

The structural design was done based on the Japanese Building Standard Law and its umbrella Orders (Ref.2). The overall design conditions are summarized in Table 1. The floors for the mixed and steel systems were assumed to be reinforced concrete slabs with deck plates which are used only for forms. In addition, the slabs of both the systems were designed to work compositely with steel girders. Interior and exterior walls, stairs, penthouses and parapets were not considered, since this assumption made the designings as well as the comparisons of the systems easier and clearer.

Results of Design and Discussions Span length and column dimensions: Interior space, for instance of marketing buildings, could be utilized more effectively as the span length increases and the dimensions of the column section decrease. The column sizes of the simulated buildings are listed in Table 2 as an equivalent width, the square of which is equal to the sectional area of the columns, where the thickness of the fire protective covers, 4cm, is considered for the steel system. The ratios of the axial forces of the columns to the axial yield forces of the columns are also listed in the table, where the reinforcing bars are neglected in the estimation of the column yield force.

As seen from Table 2, there is no significant difference in column dimensions between the mixed and reinforced concrete systems. The column sizes in the steel system are quite smaller than those of the other systems even including the thickness of the fire protective covers. The column axial force ratios of the mixed system are a little smaller than those of reinforced concrete owing to the light weight of floor system. The ratios of the steel structure system are largest among those of the three systems.

Story stiffness: The story drift angles of the designed buildings, subjected to the design seismic force of 20% of the building weight, are summarized in Table 2. As the span length becomes longer, the story drift angles have a tendency to increase in all systems. The maximum story drift angle of the mixed system is 1/375 radians, and those of the steel system and the reinforced concrete system are 1/214 and 1/577 radians, respectively. The relative ratio of the story stiffness among the three systems is; mixed, steel and reinforced concrete = 0.65, 0.37 and 1.0. That is, the story stiffness of the mixed system is improved by 75% of that of the steel system. This means that the mixed system is suitable for such buildings as hospitals which usually require high stiffness under medium earthquakes.

Story height and weight of the buildings: In general, reducing the story height makes it possible that more stories can be accommodated in the fixed total height of a building. From this respect, the story height and the depth of the girder are also summarized in Table 2, where the thickness of the fire protective covers under the steel girders is included. As the span length becomes longer than 10m, the girder depth significantly increases in the reinforced concrete system. This value, 10m, would be a practical limit of the span length for reinforced concrete system.

At least in Japan, almost all lands in and around big cities have been already developed and used up, so that there is a strong need for constructing new buildings on sites with rather weak ground such as a reclaimed ground. For this purpose, the reduction of building weight is effective. The weight per unit floor area of the designed buildings are listed in Table 2. The mixed system is rather light in weight, and would be advantageous in this respect.

Cost implications: The construction cost per unit floor area, which is estimated on the basis of the Japanese usual unit prices at Feb. 1987, are summarized in Table 2, where the cost for concrete work, rebar work, forming work, structural steel work and fire protective covers work are considered. The reinforced concrete system marks the lowest cost among the three systems over all simulated span lengths.

From the above discussions, it should be emphasized that the mixed system showed both the advantages of reinforced concrete and steel systems, though it is somewhat inferior to the reinforced concrete system in construction cost. Also, it can be noticed that the reasonable span length for this mixed system might be 10m or longer, because the reinforced concrete system is not always applicable to buildings with long spans. Further, it is clarified that this system needs less girder depth than that of steel system, because of the high rotational stiffness of the columns of the mixed system. These results obtained from the design simulations on the three story buildings could be maintained for higher buildings.

STRUCTURAL PERFORMANCE

Review of Previous Test Results and Hysteresis Model The seismic experiments on cruciform girder-to-column subassemblages (Ref.3), which were performed previously by the authors, can be summarized as follows; the diagonal crack strength in panel-zones showed two or three times higher than the calculated one, the ratios of the maximum strengths to the calculated ones were all larger than 0.9, and the critical shear drift angle of the panel-zone was at least 0.025 radians. The observed hysteresis loops can be approximated as a simple hybrid model consisting of elastic-perfectly plastic and slip models as shown in Fig.2.

Vibration Model of the Designed Mixed Building A shear type lumped mass model was employed as a vibration model in time-history dynamic response analyses as shown in Fig.3. The hysteresis model was assumed to be the hybrid one as shown in Fig.2, where the stiffnesses and yield strengths were accorded to those of the designed buildings. The critical story drift angle brought about only by the plastic behavior of the panel-zone was estimated by using the critical shear deformation of the panel-zone, 0.025 radians. The characteristic values for these analyses are listed in Table 3. Also, for the analyses, three past earthquake-ground-motion records were chosen as input waves, that is, El Centro N-S (1940), Taft E-W (1952) and Miyagi E-W (1978). These earthquake-ground-motion accelerograms were scaled linearly so as to have the maximum velocity response spectra of 50 kine (cm/sec) for the one mass system with the fundamental natural period T=10 sec and the damping ratio $h=1/\sqrt{2}$. The maximum accelerations scaled for El Centro, Taft and Miyagi were 403, 497 and 310 gals, respectively.

Assessment of Analytical Results and Discussions Maximum responses: Table 4 summarizes the maximum responses. Concerning the maximum story drift, the top story shows a larger story drift than the other stories,i.e., the first and second stories, exclusive of the response to the El Centro input. This means that the top story is relatively weak compared to the other stories. However, the maximum story drift, about 6 cm, is far less than the critical story drift, about 10cm, based on the critical panel-zone deformation, 0.025 radians (Table 4). Fig.4 shows an example of the obtained hysteretic loops.

Damage concentration: The ratios of the plastic energy absorbed into each story to the whole plastic energy are listed in Table 5. From this table, it can be seen that the top story absorbed a larger amount of energy than the other stories in the responses to the Taft and Miyagi inputs. For the El centro input, on the other hand, the damage concentrated into the second story. This damage concentration peculiarity is mainly due to the strength distribution along the height of buildings.

Here, the yield strengths along the height were on the basis of the natural period calculated by a simple design formula recommended by the current design code (Ref.2). Because the natural period of the designed mixed building was apparently larger than that estimated by the simple design formula, the real response of the top story increased unexpectedly. Therefore, if the best suited strength distribution is set by using the real natural period, these damage concentration can be lessened or avoided.

From the above discussions, it is verified that the designed mixed systems have sufficient seismic performance. It is also made clear that the damage concentration into the top or second story can be lessened by using the realistic natural periods that determine the strength distribution along the height of the building. In this paper, the dynamic response analyses for the case where the joint panel yielding occurs prior to the yielding of columns and girders were carried out. Actually, however, the yielding of columns and girders sometimes would occur prior to the joint panel yield owing to the accidental deviation of material strength or depending on design intention. To this case, previous extensive research results on reinforced concrete and steel systems are applicable. On the other hand, in the case where the yielding of fragile column and ductile girder are developed at the same time, before joint panel yielding, more complicated behavior in each story can be anticipated; it is hoped to investigate further this issue.

CONCLUSIONS

The design simulation study clarified the high structural usability of the mixed system for practical structures, that is, it possesses both the advantages of reinforced concrete and steel in various aspects. Also, dynamic response analyses showed sufficient seismic performance of the mixed system. The above conclusions imply the high feasibility of the advanced mixed system for practical use.

REFERENCES

1. Civil Engineering, ASCE, Vol.56, No.8, August 1986, pp42-45
2. The Building Standard Low of Japan, The building Center of Japan, July 1986
3. Izaki,Y. Yamanouchi,H. Nishiyama,I. and Fukuchi,Y., "Seismic Behavior of Girder-to-Column Connections Developed for An Advanced Mixed Structure System", Proceedings of the 9th WCEE, August 2-9, 1988, Tokyo-Kyoto, JAPAN

Table 1 Design Conditions

System	mixed, steel, reinforced concrete (moment resisting frame)				
Dimen-sions	3x3 bay, 3 stories clear story height: 2.9m longitudinal span: 8,10,12,14m transverse span: 6m				
Dead Load	floor mixed,steel metal deck + RC slab t=107.5mm reinforced concrete RC slab t=150mm interior/exterior walls, stairs, pent houses and parapets are not considered				
Live Load	roof floor 60kg/m2 2,3 floor 130kg/m2 (for seismic design)				
Mate-rials	steel SS41(Japan Industrial Standard) rebar SD30(JIS) for slab SD35(JIS) for column,girder concrete Fc=210kg/cm2				
Bearing Power	20tonf/m2 (for permanent load)				
Base Shear Coefficient		8x6	10x6	12x6	14x6
	Mixed,RC	0.3	0.4	0.4	0.4
	Steel	0.25	0.25	0.3	0.25
Specification ;	Building Standard Law of Japan				
Miscellaneous ;	Steel girder is designed compositely with RC slab				

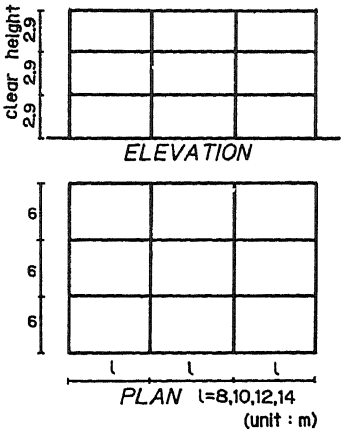


Fig.1 Prototype of Model Building

Table 2 Summarized Characteristics of Designed Buildings

Item	System Span Length (m)	Mixed 8	 10	 12	 14	Steel 8	 10	 12	 14	Reinforced concrete 8	 10	 12	 14
Column Size (mm)	3rd	500	548	592	714	380	430	480	480	500	524	598	794
	2nd	550	574	620	714	380	430	480	480	550	574	648	794
	1st	600	600	648	714	380	430	480	480	600	624	698	794
Axial Force Ratio (%)	3rd	3.2	3.9	4.0	3.4	7.4	8.0	8.4	7.4	5.1	6.0	5.9	4.9
	2nd	6.1	7.1	7.3	6.6	11.2	12.1	12.6	11.2	8.5	9.9	10.0	9.8
	1st	7.8	9.7	12.0	9.9	12.9	13.9	18.8	16.7	10.8	12.6	13.0	14.7
Story Height (Girder Depth) (m)	3rd	3.50 (0.40)	3.70 (0.60)	3.70 (0.58)	3.70 (0.59)	3.60 (0.50)	3.70 (0.60)	3.70 (0.58)	3.80 (0.69)	3.60 (0.70)	3.75 (0.85)	4.00 (1.10)	4.40 (1.50)
	2nd	3.55 (0.45)	3.70 (0.60)	3.70 (0.58)	3.70 (0.59)	3.60 (0.50)	3.70 (0.60)	3.70 (0.58)	3.80 (0.69)	3.65 (0.75)	3.75 (0.85)	4.00 (1.10)	4.40 (1.50)
	1st	3.55 (0.45)	3.70 (0.60)	3.70 (0.58)	3.70 (0.59)	3.60 (0.50)	3.70 (0.60)	3.70 (0.58)	3.80 (0.69)	3.70 (0.80)	3.75 (0.85)	4.00 (1.10)	4.40 (1.50)
Story Drift Angle (radian)	3rd	1/447	1/596	1/633	1/602	1/324	1/376	1/411	1/474	1/829	1/791	1/1031	1/1406
	2nd	1/375	1/438	1/467	1/480	1/214	1/282	1/307	1/340	1/645	1/577	1/741	1/864
	1st	1/543	1/527	1/541	1/582	1/307	1/306	1/301	1/328	1/705	1/594	1/722	1/809
Weight(tonf/m2)		1.00	0.99	0.98	1.02	0.91	0.92	0.91	0.93	1.33	1.33	1.44	1.73
Cost(x10^{4}yen/m2)		1.93	2.03	2.07	2.21	2.22	2.25	2.24	2.45	1.64	1.64	1.76	2.15

Table 3 Characteristic Values of Lumped - Mass Models

Case		6x8	6x10	6x12	6x14
Elastic Stif. (tonf/cm)	3rd	94.7	155.0	198.4	222.5
	2nd	133.1	189.7	243.4	294.8
	1st	234.8	282.7	349.3	430.8
Yield Strength (tonf)	3rd	129.2	187.2	222.2	271.3
	2nd	216.2	311.7	369.4	451.0
	1st	285.3	408.6	484.0	588.6
Weight (tonf)	3rd	237	297	357	416
	2nd	212	265	318	370
	1st	212	265	318	370
Ultimate Disp. (cm)	3rd	9.90	10.42	10.35	10.39
	2nd	10.13	10.70	10.58	10.53
	1st	9.72	10.42	10.39	10.32
1st Mode Natural Period(sec)		0.537 (0.212)*	0.510 (0.222)	0.497 (0.222)	0.490 (0.222)
Hysteresis Model		Elastic perfectly plastic (30%) + Slip (70%)			

* Values in the parentheses are recommended by Japanese Building Standard Law.

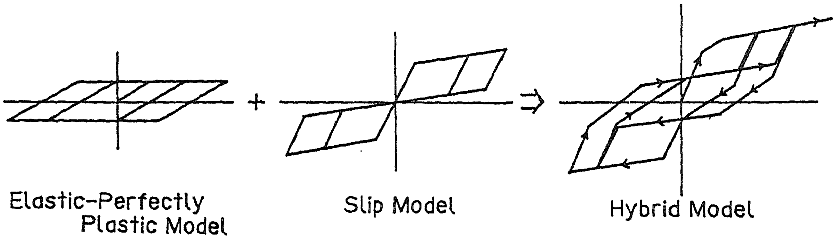
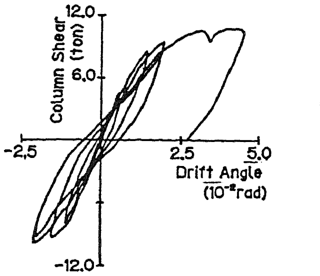


Fig.2 Hysteresis Model for Analysis



Experimental Hysteresis Curve to be Compared with Hybrid Model

Table 5 Plastic Energy Distribution

Input	Wave	El Centro	Taft	Miyagi
6x8m	3rd	40.0	82.0	81.9
grid	2nd	52.0	13.0	15.8
	1st	8.0	5.0	2.2
6x10m	3rd	26.6	79.1	71.7
grid	2nd	55.5	17.2	20.8
	1st	17.8	3.7	7.5
6x12m	3rd	23.9	78.9	72.9
grid	2nd	53.2	17.2	20.5
	1st	22.9	3.9	6.7
6x14m	3rd	29.2	71.4	66.2
grid	2nd	52.6	24.5	29.2
	1st	18.2	4.1	4.6

unit(%)

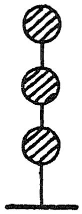


Fig.3 Lumped Mass Model

Table 4 Maximum Responses

Input	Wave	El Centro			Taft			Miyagi		
		acc. (gal)	vel. (kine)	disp. (cm)	acc. (gal)	vel. (kine)	disp. (cm)	acc. (gal)	vel. (kine)	disp. (cm)
	3rd	1014	96.0	5.30	931	68.6	5.85	635	57.9	5.85
6x8m	2nd	695	62.2	4.78	763	41.3	2.60	613	37.7	2.44
grid	1st	555	24.3	1.76	499	18.3	1.53	369	12.3	1.46
	3rd	1021	88.8	3.47	962	69.3	4.38	732	59.8	5.27
6x10m	2nd	819	64.2	4.48	945	45.2	2.27	650	41.3	2.83
grid	1st	669	29.1	2.68	523	23.0	1.81	417	20.8	2.08
	3rd	973	87.4	3.08	960	66.6	4.39	813	56.6	4.63
6x12m	2nd	865	60.7	4.47	932	45.0	2.57	648	40.6	2.72
grid	1st	717	28.7	2.79	539	21.7	1.81	419	19.9	1.98
	3rd	944	89.9	3.10	1045	66.8	4.01	805	72.3	4.41
6x14m	2nd	884	60.1	4.08	882	45.5	2.91	672	47.5	2.70
grid	1st	922	28.7	2.75	543	21.4	1.74	451	20.6	1.62

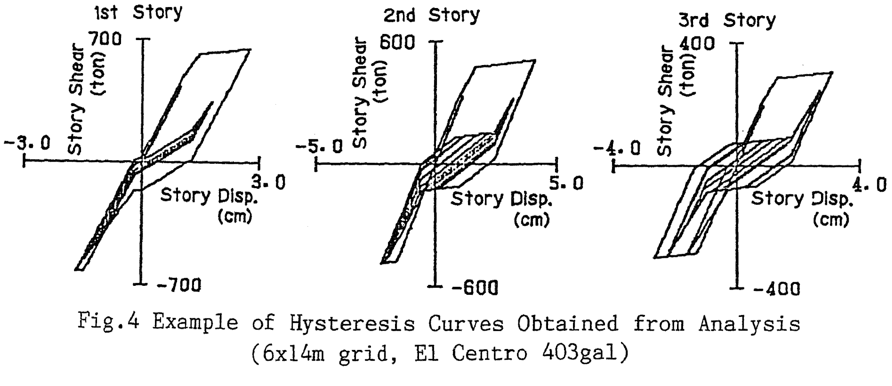


Fig.4 Example of Hysteresis Curves Obtained from Analysis
(6x14m grid, El Centro 403gal)