An application of high strength steels to earthquake resistant buildings

Autor(en): **Akiyama, Hiroshi**

Objekttyp: **Article**

Zeitschrift: **IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht**

Band (Jahr): **10 (1976)**

PDF erstellt am: **12.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-10462

An Application of High Strength Steels to Earthquake Resistant Buildings

Utilisation des aciers à haute résistance dans des bâtiments résistants aux tremblements de terre

Anwendung hochfester Stähle in erdbebensicheren Bauten

HIROSHI AKIYAMA
Associate Professor
University of Tokyo
Tokyo, Japan

1. INTRODUCTION

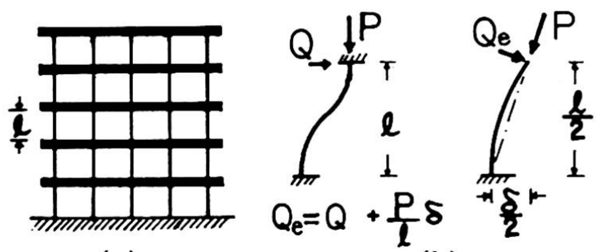
One of the structural performances requisite for earthquake resistant structures is absorption capacity of vibrational energy exerted by earthquakes. Sources of energy absorption are found in inelastic deformations of structural members and other damping effects and to evaluate the inelastic deformation is essentially necessary to economically proportion steel structures.

Ordinary structural steel can develop considerable amount of inelastic deformation, provided that the structural members are properly kept from any types of instability . High-strength steels, however, show less inelastic deformability as stated in Theme report Va. Therefore it seems less advantageous to make use of the poor inelastic deformability of high-strength steels.
It may be rather more efficient to make use of the large elastic deformability and high strength of them.

Combined use of high-strength steels and usual steels may allow preferable structural performances in earthquake resistant structures, especially in tall buildings. In such composite structures where high-strength steels form a continuous structural component besides usual steels, the structural component composed of high-strength steels can behave elastically, while components composed of usual steels with less elastic deformability may undergo plastic deformations and can absorb vibrational energy. As a whole, the co-existence of these two different steels is likely to facilitate to evenly disperse plastic deformations over the whole structure, preventing the collapse of the structure caused by concentration of damages into one story. Only confined use of high-strength steels may be sufficient to attain the aim.

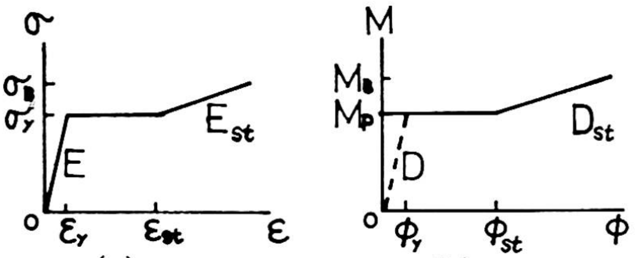
2. ASSESSMENT OF INELASTIC DEFORMABILITY OF HIGH-STRENGTH STEELS

In Fig.1 the simplified structural model for a multi-storied structure subjected to seismic forces is shown, where deformable elements are represented by columns clamped by rigid beams. As shown in Fig.1(b), structural behavior of the structure is reduced to that of the cantilever column with the length of one half of the story height. The inelastic behavior of the cantilever steel column can be well predicted by a simple theory allowing for the strain-hardening of the steel(1). Stress-strain relationship of the steel may be expressed by a tri-linearized relation as shown in Fig.2(a). Moment-curvature relationship for usual sectional shapes such as H-shapes and structural tubes can be readily obtained from $\sigma-\varepsilon$ relation, the inelastic part of which is expressed by a



(a) (b)

Fig.1 Simplified Structural Model



(a) (b)

Fig.2 Properties of Steels

bi-linear relation as shown in Fig.2(b). In Fig.2(b) M_p and M_B mean the fully plastic moment and the ultimate moment capacity of a section respectively and can be expressed as

$$M_p = A\times M_{p0}(1-p), \qquad M_B = A\times M_{p0}(1/Y-p), \qquad (1)$$

where M_{p0}=fully plastic moment under pure bending, $p=P/P_y$, P=axial force, P_y =yield axial force, Y=yield ratio of the material= σ_y/σ_B , A=constant.

Flexural rigidity in plastic range, D_{st} and the curvature at the onset of the strain-hardening, ϕ_{st} can be determined as

$$\text{for } p\le 0.5, \quad D_{st}=DE_{st}(1+2p)/E, \quad \phi_{st}=\phi_0,$$
$$\text{for } p>0.5 \quad D_{st}=2DE_{st}/E, \quad \phi_{st}=\phi_0/(2-2p), \qquad (2)$$

where $\phi_0=\phi_y(\varepsilon_{st}-\varepsilon_y)/\varepsilon_y$, D=flexural rigidity in elastic range=EI, $\phi_y=M_p/D$.

Then the inelastic deformation of the cantilever column can be calculated from the following formula.

$$\delta_p=\left(\frac{a-1}{2}\frac{D}{D_{st}}+b\right)\left(\frac{a^2-1}{2a^2}\right)\frac{\ell^2\phi_y}{2}, \qquad Q_e=\frac{2aM_p}{\ell}, \qquad a\ge 1, \qquad (3)$$

where $b=\phi_{st}/\phi_y$, a=stress increase ratio beyond M_p, and the maximum value of a at the ultimate state can be written from Eq(1) as

$$a_m = M_B/M_p=(1/Y-p)/(1-p) \qquad (4)$$

Since for most of structural steels Q_e- δ_p relation becomes almost linear, Q_e-δ relation may be simply expressed by a bi-linear relation. Thus by non-dimensionalizing Q_e by $Q_{ye}(=2M_p/\ell)$ and δ by $\delta_y(=Q_y\ell^3/12D)$, Q_e- δ relation is obtained as shown Fig.3(a), where μ_m means dimensionless ultimate plastic deformation capacity(ductility) and μ_m is given by the following equation.

$$\mu_m=\frac{\delta_p}{\delta_y}=3\left(\frac{a_m-1}{2}\frac{D}{D_{st}}+b\right)\left(\frac{a_m^2-1}{2a_m^2}\right) \qquad (5)$$

For an example two typical structural steels(a mild steel and a high-strength steel) are compared in their structural behavior in the inelastic range. Material properties of them are tabulated in Table 1.

Grade	σ_y t/cm²	σ_B t/cm²	Y	ε_{st}	E_{st}
mild steel (SS41)	2.4	4.1	0.59	11 ε_y	E/30
high strength steel(SM58)	5.0	6.0	0.83	5 ε_y	E/50

Table 1. Mechanical Properties of Steels

High-strength steel is characterized by it's high yield ratio.

In Fig.3(b) and 3(c) the results of calculation are shown. In Fig.3(b) the slope of inelastic range relative to that of elastic range is shown. In Fig.3(c) the ductility is plotted. From these figures it can be seen that the slope of the inelastic range is not likely to be affected by the difference of the steels, ranging about 5% of the slope in elastic range and consequently the ductility is considerably affected by the yield ratio of the material.

Thus the ductility of the high-strength steel will be considerably reduced according to the increase of the yield ratio and should not be reliable sources of energy absorption during earthquakes. On the contrary mild steels can develop fairly large ductility even under high axial compression.

Substantial horizontal resistance of the column is affected by P-δ effect and is expressed by

$$Q=Q_e-P\delta/\ell \qquad (6)$$

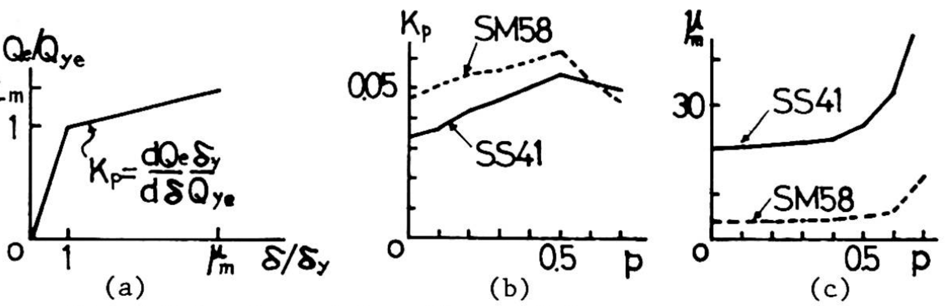


Fig.3 Behavior of Cantilever Columns

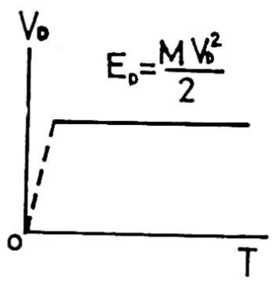


Fig.4 Energy Input

3. GENERAL BEHAVIOR OF BUILDINGS UNDER EARTHQUAKES

Housner assumed that energy input contributable to structural damages exerted by an earthquake can be approximately expressed by

$$E_D=0.5M\dot{y}^2_{e\,max}, \quad (7)$$

where E_D=energy input causing damages, M=total mass of the structure, $\dot{y}_{emax}$=velocity response spectrum of elastic system(2).

A general law on vibrational systems can be written as

$$W_e+W_P+W_h=W_E \quad (8)$$

where W_E=total energy input exerted by an earthquake, W_P=energy absorption due to accumulated plastic work(structural damages), W_h=energy absorption due to damping, W_e=elastic vibrational energy.

E_D may correspond to W_P+W_e. Through vast amount of numerical analyses on inelastic vibrational systems with various types of restoring force characterisyics, each energy component in the above equation was evaluated and Housner's assumption was verified to be applicable to general structures(3). Consequently the amount of energy contributable to structural damages is scarecely affected by the difference of the structural forms and averagingly E_D, when expressed in a velocity through conversion given below, may be considered to be constant over a wide range of fundamental natural periods of the structures except a narrow range of shorter natural period as shown in Fig.4.

$$V_D=\sqrt{2E_D/M} = \sqrt{2(W_P+W_e)/M} \quad (9)$$

To controle vertical distribution of damages is one of the essentials in the aseismic design of multi-storied buildings subjected to a certain amount of energy input. When the vertical strength distribution is well balanced, the damages may be evenly dispersed. Otherwise, the damages concentrate into relatively weak stories. Since distribution of damages are seriously dependent on the vertical strength distribution, the effect of probable deviation of the strength distribution from the aimed one must be taken into account and the structural robustness of the tall building must be examined under such a disadvantageous condition encountered by the decrease of strength in a story.

4. BEHAVIOR OF COMPOSITE STRUCTURES UNDER EARTHQUAKE

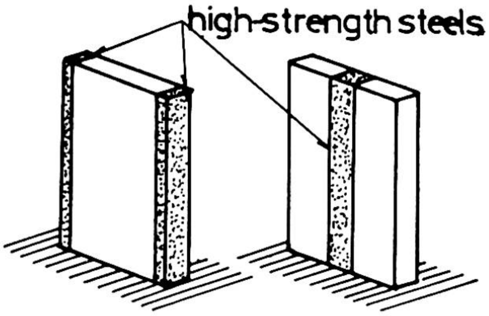
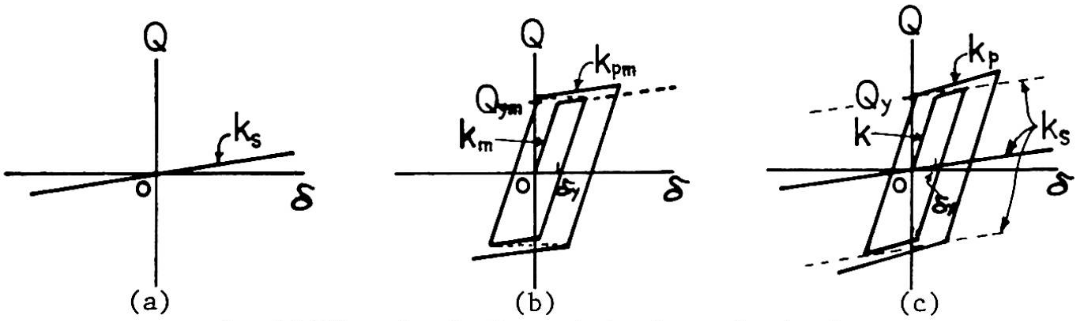


Fig.5 Composite Structure

A possible combination of usual steel components and high-strength steel components is illustrated in Fig.5. High-strength steel components extending vertically are tightly connected to mild steel components through rigid slabs.

Restoring force characteristics for high-strength steels may be considered to be elastic within the limit determined by their yield strength. P-δ effect being a negative linear action as seen in Eq(6) can be included in the property of high-strength steel components. Thus the characteristics for high-strength steels involving P-δ effect may be depicted as shown in Fig.6(a) where δ and Q denote relative story displacement and restoring force in the story. The restoring force characteritics for mild steels can be readily constructed from the bi-linear load-deflection relation under monotonic loading as shown in Fig.6(b), where the broken line



$k= dQ/d\delta$, $Q_y=Q_{ym}+k_s\delta_y$, $k=k_m+k_s$, $k_p=k_{pm}+k_s$

Fig.6 Restoring Force Characteristics of Composite System

shows the monotonic Q-δ relation. These are drawn according to the rule that the inelastic parts in each cycle of loading in one loading domain(negative or positive) connected sequentially should coinside with the inelastic curve in the monotonic loading(4). Overall restoring force characteristics in one story may become like that shown in Fig.6(c).

According to the conventional numerical technique, the dynamic responses of composite structures were carried out. Applied models are five-mass systems with 1 sec of fundamental natural period and the used accelerogram is of El Centro May 1940-NS Component, maximum value of which is 320 gals. No other damping source except inelastic deformations was considered.

Parameters used in analyses are specified in Table 2 where α denotes yield shear coefficient defined below.

$$\alpha = Q_y / W \,, \qquad (10)$$

where W=total gravity load above the story considered,

Q_y=yield strength of the story.

m_i/m_1	α_2/α_0	α_3/α_0	α_4/α_0	α_5/α_0	k_2/k_1	k_3/k_1	k_4/k_1	k_5/k_1	comment
1.0	1.1	1.25	1.56	2.0	0.87	0.73	0.6	0.4	common for all cases

Case	No.1	No.2	No.3	No.4	No.5	No.6
k_{pi}/k_i	0.0	0.1	0.2	0.05	0.15	0.25
k_{si}/k_i	0.0	0.1	0.2	0.0	0.1	0.2
comment	elastic -plastic	composite without strain hardening		composite with strain hardening		
α_1/α_0	1.0, 0.8, 0.7 for all cases					

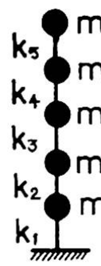


Table 2. Parameters Used in Response Analysis

Dynamic responses of those models were calculated by varing α_0 from 0.1 to 0.6. Special attention was paid to the responses of the first story where the yield strength was changed in three steps as shown in Table 2. Maximum story displacement and accumulated plastic deformation in both positive and negative directions were obtained and non-dimensionalized responses were defined as

$$\mu_{1\pm} = |\delta_{1\pm}|/\delta_{y1} \,, \quad \eta_{1\pm} = \Sigma\,|\Delta\delta_{p\pm}|\,/\delta_{y1} \qquad (11)$$

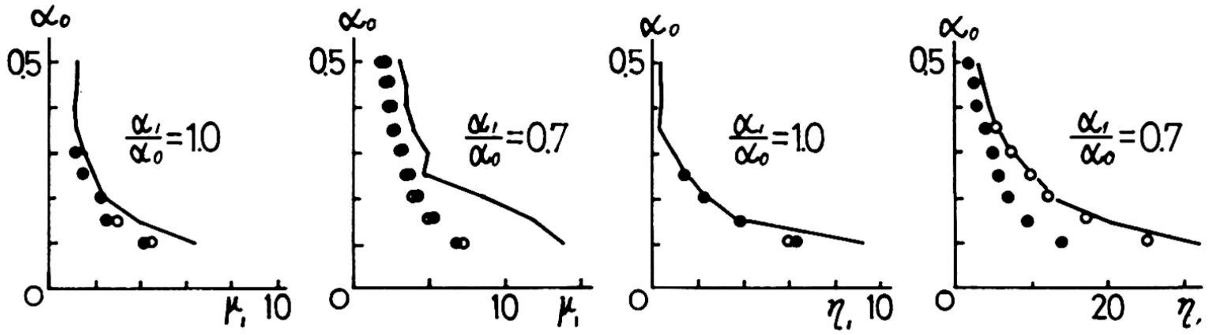
where δ_1 =maximum deflection of the first story into one direction,

$\Delta\delta_p$=plastic deformation increment of the first story into one direction.

In Fig.7 some typical responses for composite structures are shown. In Fig.7(a) the greater value of $\mu_{1\pm}$ are plotted. It can be seen that when the strength of the story is reduced by 30%, the maximum deflection of non-composite elastic-plastic system increases considerably. The composite structure, however, can be kept in small increase of deflection by only 10% of cooperative action of high-strength steels(k_s/k=0.1 in No.5).

In Fig.7(b) the greater value of $\eta_{1\pm}$ is plotted. The decrease of strength of the first story produces severe energy concentration in elastic-plastic system and the composite structures without strain-hardening are also likely to undergo the remarkable energy concentration comparable to that in non-composite structures. The composite structure with strain-hardening, however, can do without suffering such a large energy concentration, and only 10 or 15% of the

cooperative action of the high-strength steels with mild steels enables the enrgy concentration to reduce by half.
In Fig.8 the correspondence between $(\mu_+ + \mu_-)/2-1$ and $(\eta_+ + \eta_-)/2$ is shown. This relation may be generally used to estimate μ from η and vice versa as mentioned afterward.
It can be concluded that the hazardous energy concentration induced by the probable decrease of the strength may be overcome by the robust nature of the composite structure.



(a) (b)

o k_p/k =0.2, k_s/k =0.2 (No.3)
• k_p/k =0.15, k_s/k =0.1 (NO.5)

Fig.7 Responses of Composite Structures

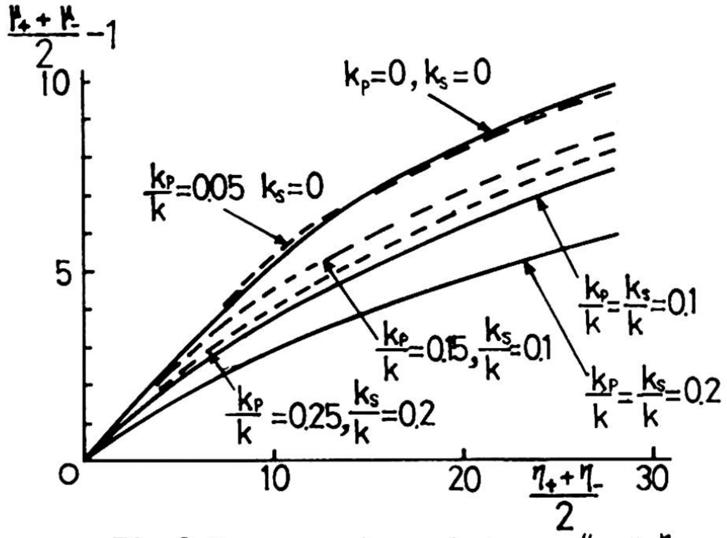


Fig.8 Correspondence between μ and η

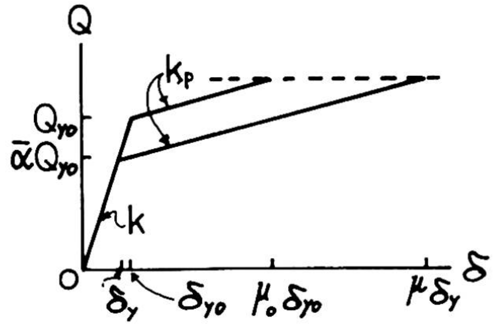


Fig.9 Maximum Deflection

5. ESTIMATION OF RESPONSES OF COMPOSITE STRUCTURES

The response of the composite structures may be estimated from that of the elastic-plastic system with same strength distribution by making an assumption that $\mu_+ = \mu_-$ and $\eta_+ = \eta_-$.
By taking account of the equivalence in accumulated plastic energy into two systems with same strength, η of the composite system can be converted from the response of the elastic-plastic system, η_{ep} through the following equation.

$$\eta\left(1-\frac{k_p-k_s}{k-k_s}\right)\left[2\left(1-\frac{k_s}{k}\right)+\eta\frac{k_p-k_s}{k}\right]=2\eta_{ep}, \qquad (12)$$

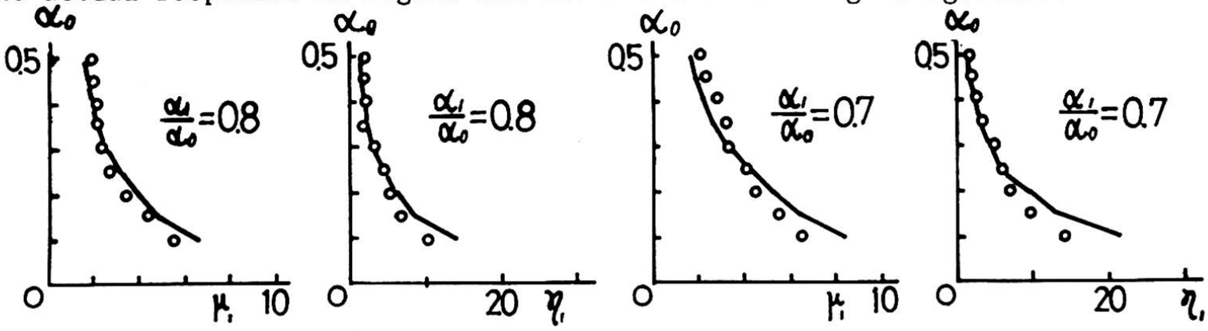
where k, k_p and k_s are rigidities defined in Fig.6.
μ can be readily obtained from Fig.8.
The maximum displacement of the story where some decrease of the strength happened to occur can be estimated from the original undegraded system under the assumption that the maximum lateral force of the degraded system does not exceed that attained by the original system. Referring to Fig.9, the possible maximum response of the degraded story can be obtained as

$$\mu = \frac{k}{k_p}\frac{1}{\bar{\alpha}}\left[\frac{k_p}{k}(\mu_o-1)+1-\bar{\alpha}\right]+1, \quad \mu_o \geq 2.0,\ k_p/k \geq 0.1. \qquad (13)$$

η can be also determined from Fig.8. For smaller values of μ, the above equation will give overestimation. However, for smaller value of η, $\alpha - \eta$ relation can be extrapolated from the already obtained by the next equation(3).

$$\alpha^2 \eta = \text{constant} \qquad (14)$$

Thus alternatively smaller values of μ can be determined again from Fig.8. To verify the above mentioned procedure, the response of the composite structure was predicted by using only the averaged response of the elastic-plastic system(No.1), $(\mu_{1+}+\mu_{1-})/2$ and $(\eta_{1+}+\eta_{1-})/2$. Predicted values are compared with the actual responses in Fig.10 and are found to be in good agreement with them.



— prediction   o Responses of No.5(k_p/k =0.15, k_s/k=0.1)

Fig.10 Predicted responses of Composite Structure

REFERENCES

(1) Kato,B. and Akiyama,H., Inelastic Bar Subjected to Thrust and Cyclic Bending, Proc. ASCE, ST1, January 1969

(2) Housner,G.W., Limit Design of Structures to Resist Earthquakes, 1st WCEE,1956

(3) Kato,B. and Akiyama,H., Energy Input and Damages in Structures Subjected to Severe Earthquakes, Trans. AIJ, No.235, Sept. 1975(in Japanese)

(4) Kato,B. and Akiyama,H., Theoretical Prediction of the Load-Deflection Relationship of Steel Members and Frames, IABSE Sym. Lisboa 1973

SUMMARY - It is required for earthquake resistant tall buildings to be equiped with large energy absorption capacity and to be prevented from hazardous energy concentration. The proposed hybride structure consisting of principal mild steel components and secondary high-strength steel components was found to exhibit preferable robustness during earthquakes. It was also shown that the response of the composite structure can be well predicted taking into account the response of the fundamental elastic-plastic systems.

RESUME - Les maisons hautes susceptibles de résister aux tremblements de terre doivent être capables d'absorber de grandes quantités d'énergie tout en évitant leur concentration . La construction hybride proposée dans cet article, composée d'éléments principaux en acier doux et d'éléments secondaires en acier à haute résistance, a présenté la meilleure résistance lors de tremblements de terre. Les réactions de la construction hybride peuvent être déterminées à l'avance en fonction du comportement élasto-plastique du système.

ZUSAMMENFASSUNG - Die erdbebensicheren Hochhäuser müssen grosse Energiemengen absorbieren, welche sich nicht konzentrieren dürfen. Das im Bericht beschriebene hybride Tragwerk aus Hauptelementen aus Stahl St 37 und Nebenelementen in hochfestem Stahl, hat das beste Verhalten gegen Erdbeben gezeigt. Die Widerstandsfähigkeit des hybriden Tragwerkes kann im voraus anhand des elastoplastischen Verhaltens des Systems berechnet werden.