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SEISMIC DAMAGE REDUCTION DUE TO UPLIFT: SHAKING TABLE TESTS OF A SINGLE-STORY FRAME MODEL ON RIGID GROUND

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Abstract

The seismic damage reduction effect of rocking motion accompanied by uplift has been studied by many researchers for buildings and bridge piers.

In this study, a series of the shaking table tests on a single-story steel frame model are conducted to verify the reduction effect due to uplift.

The test specimen is made of steel and composed of upper frame and base foundation which are tightly bolted together. Its height is about 600 mm and the mass is about 120 kg. The upper frame is composed of two identical one-bay two-dimensional frames with four rigid columns (circular steel pipe; $\phi 27.2\times2.3$) and two flexible beams (thin flat bars; PL30×4.5). They are connected rigidly at column tops with stacked and bolted thick flat bars (PL100×22). The connections also serve as the major mass of the specimen. The span between the columns is 300 mm, and the flexible length of beams is 200 mm. The strength capacity is adjusted by making the notches at both ends of the flexible range of beams. The strength capacity of the frame calculated by assuming plastic hinges at notch locations of beams is 0.23 in terms of story shear coefficient. The critical story shear coefficient initiating uplift motion is 0.26. The strength capacity is slightly less than the initiation of uplift. The column bases are pinned with hinges. The base foundation is stiff enough not to deform. The four supports under the base foundation are fixed to the shaking table to avoid the sliding of the specimen. The span between the supports is 200 mm.

Two base conditions are adopted in the tests: uplift allowed (UP) and not allowed (FIX).

Displacements of several points and strains of beams are measured at a sampling rate of 200 Hz. The story shear of the frame is calculated based on the measured strains of beams.

The input motion for the shaking table tests is JMA Kobe NS (1995) record. The magnitude of the acceleration is scaled down but the time is not adjusted.

From the test results, the uplift motions and higher mode vibrations are observed in UP. The peak and residual inelastic deformations are relatively small in UP, whereas they are very large in FIX. The test results demonstrate the damage reduction effect due to uplift even if calculated strength capacity of the superstructure is less than that corresponding to the initiation of uplift.

Keywords: seismic damage; reduction; uplift; inelastic deformation; higher mode

1. Introduction

Uplift accompanied by rocking motion during earthquakes is often beneficial for reducing the seismic effects and damage on structures. Following Housner's pioneering investigation [1] on the survival of slender structures in the Great Chilean earthquake in 1960, many studies have been conducted thus far [2–8]. The authors have also investigated the valuable effect of uplift through experiments and analyses [9–14].

In this study, a series of the shaking table tests on a single-story steel frame model are conducted to verify the reduction effect due to uplift.

2. Specimen and experimental procedures

2.1 Specimen

Figs. 1 and 2 show the test specimen. The test specimen is made of steel and composed of upper frame and base foundation which are tightly bolted together. Its height is about 600 mm and the mass is about 120 kg. The upper frame is composed of two identical one-bay, two-dimensional frames with four rigid columns (circular steel pipe; ϕ27.2×2.3) and two flexible beams (thin flat bars; PL30×4.5). They are connected rigidly at column tops with stacked and bolted thick flat bars (PL100×22). The connections also serve as the major mass of the specimen. The span between the columns is 300 mm, and the flexible length of beams is 200 mm. The column bases are pinned with hinges. The base foundation is stiff enough not to deform. The four supports under the base foundation are fixed to the shaking table to avoid the sliding of the specimen. The span between the supports is 200 mm.

The strength capacity is adjusted by making the notches at both ends of the flexible range of beams. The yield stress of the flexible beams, σ_y, is 339.5 N/mm^2. The strength capacity of the frame calculated by assuming plastic hinges at notch locations of beams is 0.23 in terms of story shear coefficient. The critical story shear coefficient initiating uplift motion is 0.26. The strength capacity is slightly less than the initiation of uplift.

Two base conditions are adopted in the tests: uplift allowed (UP) and not allowed (FIX). In FIX, base foundation is connected tightly to the base beam. The natural frequency evaluated by free vibration of FIX was 2.61 Hz (natural period of 0.38 s) and the damping ratio was 2.64 %.

2.2 Experimental procedures

Displacements of several points and strains of flexible beams are measured at a sampling rate of 200 Hz. The story shear of the frame is calculated based on the measured strains of beams.

Fig. 3 shows the definition of column rotation angle, R, base rotation angle, θ, and shear deformation, γ. R and θ are calculated based on the differences of measured horizontal and vertical displacements of the specimen. Shear deformation, γ, is evaluated as $\gamma = R - \theta$.

Story shear, Q_s, and story shear coefficient, C_1, of the upper frame are calculated using the sum of the shear forces of the two flexible beams, q_b, as follows:

$$Q_s = (L/h_c)\, q_b \tag{1}$$

$$C_1 = Q_s / (m_U\, g) \tag{2}$$

where L is the span of the columns (L=300 mm), h_c is the height for shear force (h_c=487 mm), m_U is the mass for the upper frame (m_U=95 kg) and g is the gravitational acceleration. The shear forces of the flexible beams are calculated based on the measured strains. The total mass of the specimen with the base foundation is 121 kg.

The input motion for the shaking table tests is the scaled JMA Kobe NS (1995) record. The amplitude of the acceleration is scaled down to 50% of the original record but the time is not adjusted. Duration time of the input motion is 20 seconds. In the tests, many levels of the input amplitude ("Input Amp." or "I.A.") was applied to the specimen. Input Amp. was from 10% to 55% (from 5% to 27.5% of the original record). The identical upper frame was used in the tests for UP and FIX. All the tests for UP were conducted first because the relatively large inelastic deformation of the upper frame was expected for FIX as shown later.

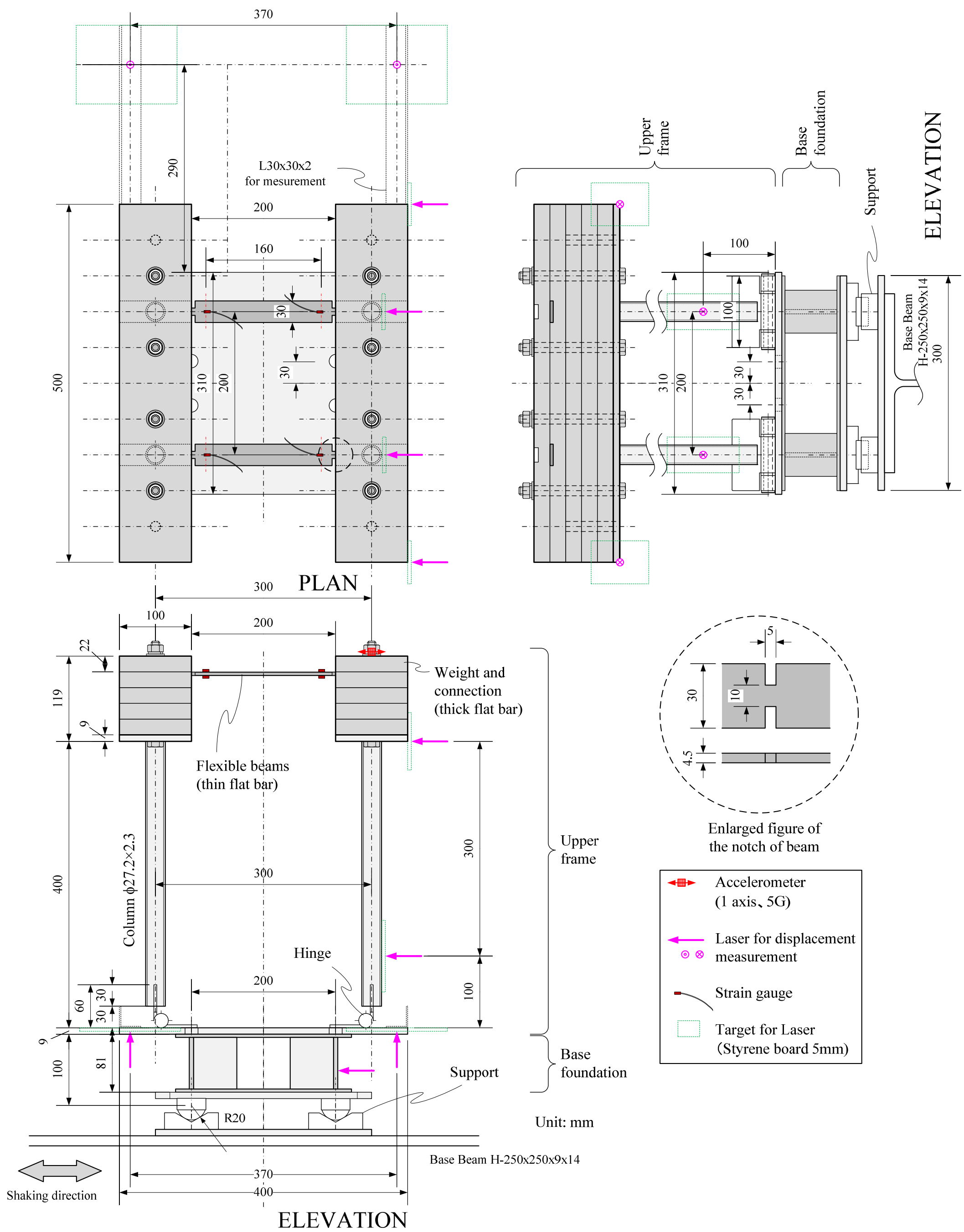


Fig. 1 – Test specimen and measurement plan

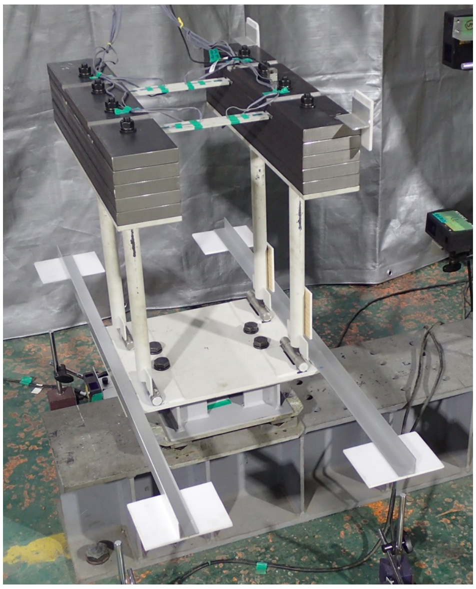


Fig. 2 – Test specimen

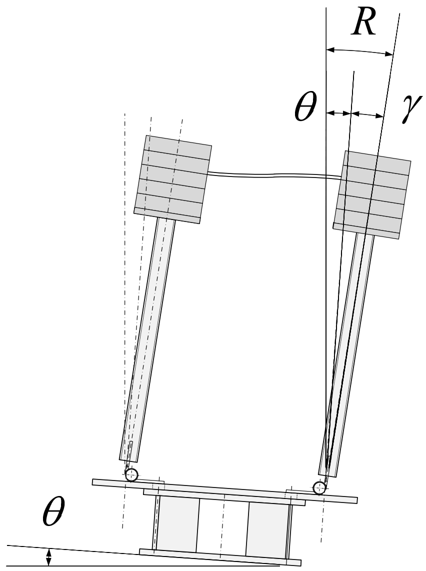


Fig. 3 – Definition of column rotation angle, *R*, etc.

3. Test results and discussion

3.1 Time histories (I.A.=50%)

Fig. 4 shows the time histories of UP and FIX responses against I.A.=50%.

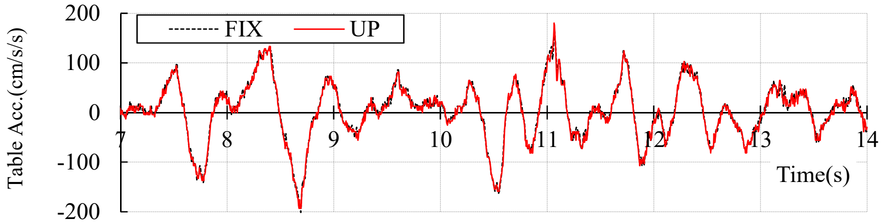
Fig. 4(a) shows the input acceleration measured at the base beam. The maximum acceleration was about 200 cm/s/s. It is confirmed that the input acceleration for UP and FIX was identical.

Fig. 4(b) shows the story shear coefficient, C_1. The peak for FIX is about 0.3 while that for UP is about 0.25. Ripples is observed in UP. They can be recognized as the effect of higher mode (the second mode during an uplift excursion) response.

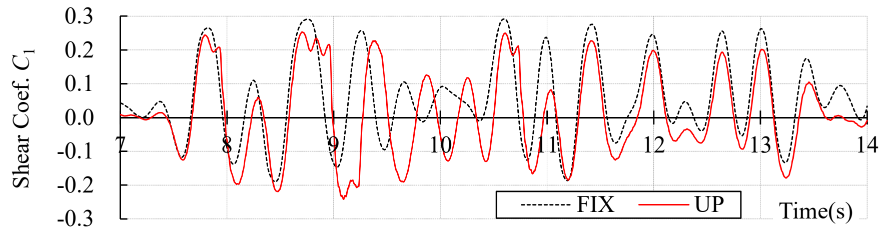
Fig. 4(c) shows the story shear deformation, γ. Relatively large initial deformation of about 0.02 in FIX is observed before the test against I.A.=50% because the inelastic deformation has been caused in the preceding tests against lower I.A. The inelastic deformation in FIX progressed further and considerably shifted to the positive side. The initial deformation in UP is also confirmed but less than that in FIX. The peak in UP is about 0.04 and ripples are also observed as those in the story shear coefficient.

Fig. 4(d) shows the column rotation angle, *R*. The response in FIX is greater than that in UP because of the initial residual deformation and the progression of the inelastic deformation. It should be noted that ripples are not observed in UP. The reason is that the higher mode in an uplift excursion has a little effect to the overall behavior of the structure.

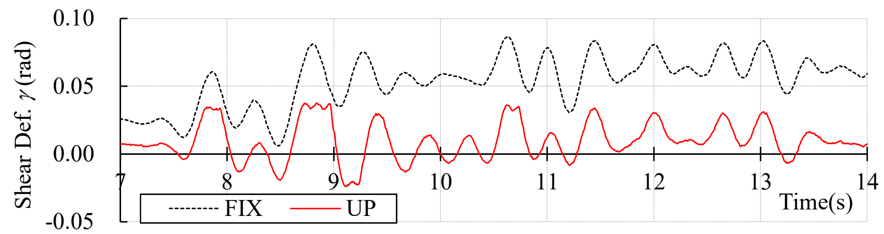
Fig. 4(e) shows the base rotation angle, θ. The peak in UP is 0.026 rad, which is about a half of the peak of column rotation angle, *R*.



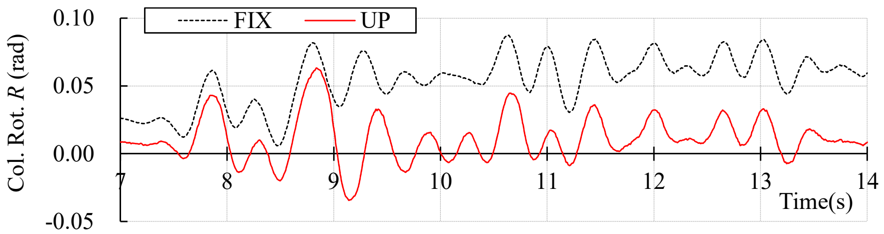
(a) Horizontal acceleration of shaking table



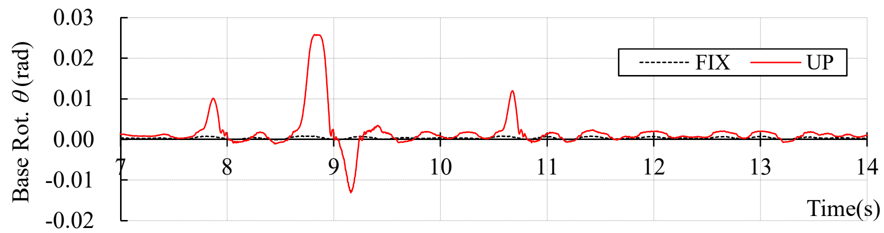
(b) Story shear coefficient, C_1



(c) Shear deformation, γ



(d) Column rotation, R

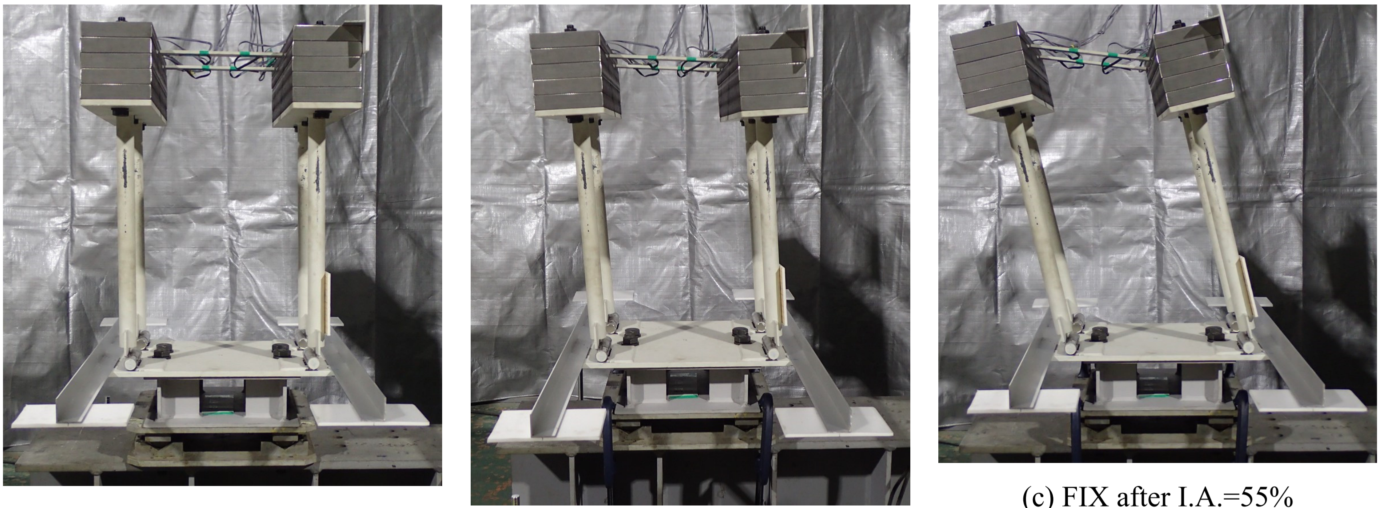


(e) Base rotation, θ

Fig. 4 – Time histories (I.A.=50%)

3.2 Effect of uplift motion on inelastic responses

Fig. 5 shows the residual deformation of the specimen after the tests. Fig. 5(a) shows UP after I.A.=50%. No residual deformation is observed. On the other hand, as shown in Fig.5 (b), the inclination to the left side is observed in FIX after the test against I.A.=50%. Allowing uplift can reduce not only the peak inelastic deformation during an earthquake but also the residual deformation after the event. Fig. 5(c) shows FIX after I.A.=55%, the maximum input amplitude in the tests. The significant residual deformation can be seen.



(a) UP after I.A.=50%　　(b) FIX after I.A.=50%　　(c) FIX after I.A.=55%

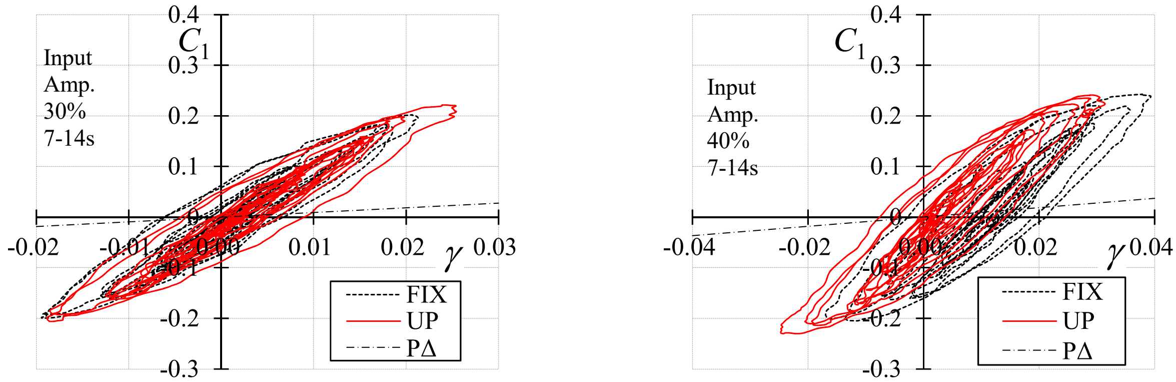
Fig. 5 – Residual deformation of the test specimen

Fig. 6 shows the relationships of the story shear coefficient, C_1, and shear deformation, γ. The dash-dot line in each figure shows the so-called PΔ effect due to the shear deformation, γ, expressed as follows:

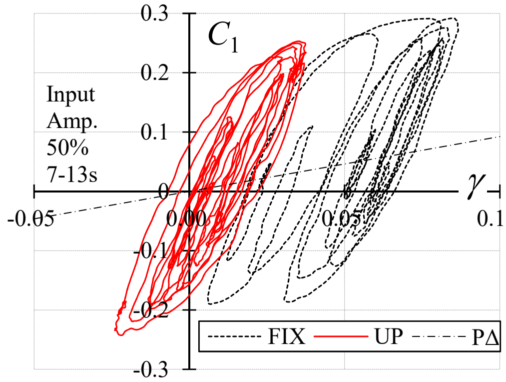
$$C_1 = (h/h_c)\ \gamma \approx 0.92\ \gamma \qquad (3)$$

where h is the height of the center of gravity (h=450 mm).

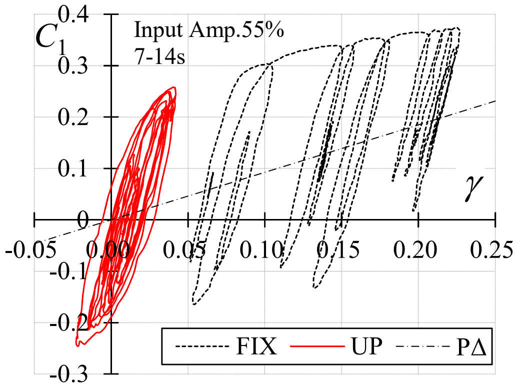
Fig. 6(a) shows the responses against the motion of I.A.=30%. The peak story shear coefficients in FIX and UP are about 0.22, which is less than the strength of the upper frame. Therefore, specimens in FIX and UP are in elastic range. Against I.A.=40%, the inelastic deformations can be seen as shown in Fig. 6(b). Fig. 6(c) shows the relations against I.A.=50%. The inelastic deformation in FIX is large, while that in UP is small. Against I.A.=55% as shown in Fig. 6(d), the deformation in FIX progresses to the positive side due to the PΔ effect. On the other hand, the deformation in UP is suppressed to the relatively small range.



(a) I.A.=30%　　(b) I.A.=40%



(c) I.A.=50%

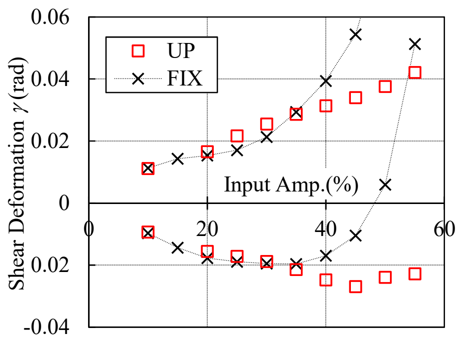


(d) I.A.=55%

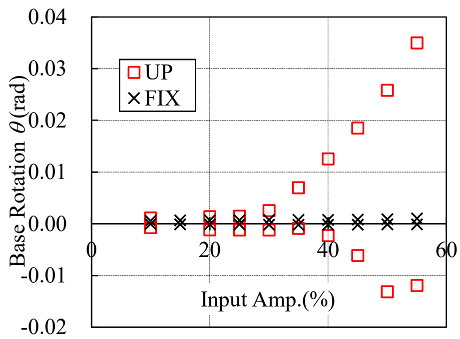
Fig. 6 – Story shear, C_1 vs. shear deformation, γ, relationships

3.3 The maximum/minimum responses and residual deformation

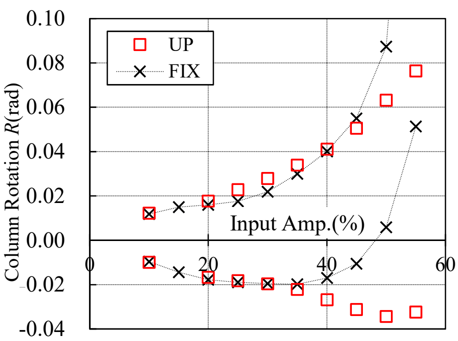
Fig. 7 shows the maximum and minimum responses. The horizontal axis of the graphs is the input amplitude I.A. Fig. 7(a) shows the shear deformation, γ. FIX is largely deformed with shift to the positive side from approximately I.A.=40%. In UP, the deformation amplitudes on the positive side are slightly larger than those on the negative side. The peak deformations in UP are almost equal or less than those in FIX. Fig. 7(b) shows the base rotation angle, θ. In UP, the uplift motions occur at I.A.=35% and above. The maximum base rotation angle grows rapidly with the increase of I.A. Fig. 7(c) shows column rotation angle, R. It should be



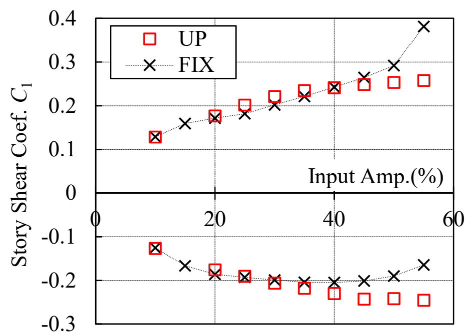
(a) Shear deformation angle, γ



(b) Base rotation angle, θ



(c) Column rotation angle, R



(d) Story shear coefficient, C_1

Fig. 7 – Maximum and minimum responses

noted that R is equal to γ in FIX. The rotations in UP are almost equal to those in FIX against I.A.=45% and below. Fig. 7(d) shows the story shear coefficient, C_1. Almost the same response is observed due to the strength of the specimen. The large response in FIX against I.A.=55% is considered to be a result of PΔ effect in large deformations.

Fig. 8 shows the absolute residual shear deformation $|\gamma_{res}|$ after each excitation. After the excitation of I.A.=55%, the residual deformations in FIX is 0.24, while that in UP is only 0.013. It is confirmed that allowing uplift has the effect of suppression on the residual deformation.

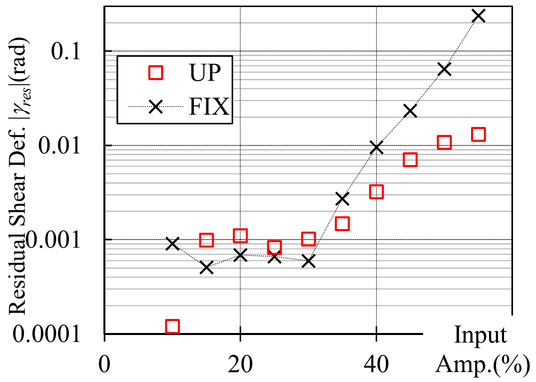


Fig. 8 – Residual shear deformation

4. Conclusions

A series of the shaking table tests on a single-story steel frame model are conducted to verify the reduction effect due to uplift. From the test results, the uplift motions and higher mode vibrations are observed in UP (uplift allowed). The peak and residual inelastic deformations are relatively small in UP, whereas they are very large in FIX (uplift not allowed). The test results demonstrate the damage reduction effect due to uplift even if calculated strength capacity of the superstructure is less than that corresponding to the initiation of uplift.

5. Acknowledgement

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