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Damage trends in residential RC building after 2015 Nepal earthquake

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Abstract

The Mw 7.9 Nepal Earthquake at AM11 : 56, April 25, 2015 (also known as the Gorkha Earthquake) resulted in a lot of injured people and caused numerous buildings, including world heritage sites, to collapse. In its aftermath, damage investigations were conducted around the nation's capital of Kathmandu Metropolitan City and Lalitpur Sub-Metropolitan City (commonly referred to as Patan). In the course of our investigation, 21 reinforced concrete (RC) residential buildings that were more than 10 floors high were examined. Some of these were under construction when the earthquake occurred. The investigation process included visual examinations, listening surveys, quick post-earthquake inspections for damaged buildings, and natural period evaluations based on microtremor measurements. This report begins with a presentation on our study objectives and the characteristics of RC high-rise residential buildings in Nepal, after which a summary of damage trends is provided. Our results show that while most of the RC frame structures examined suffered minor damage, more significant destruction was found in nonstructural infill brick walls both inside and outside inspected buildings. Damage types included shear failures as well as cracks along the masonry joints and boundary surfaces between RC frames and brick walls. It was also found that damage levels tended to be more severe in the lower floors than the upper floors. The same tendencies were noted in Japan when comparisons were made to building damage during the Great East Japan Earthquake, which occurred on the Pacific coast of the Tohoku region on March 11, 2011. Specifically, damage levels inside high-rise buildings were found to be more severe than could be seen from the outside, while numerous low-rise buildings in the examined areas showed no damage at all. Additionally, damage was found in buildings equipped with expansion joints that seemed to be caused by pounding behavior resulting from inadequate expansion joint clearance. Next, because existing methods tend to underestimate damage levels, an original method of conducting quick post-earthquake inspection of damaged buildings was proposed. It is believed that life continuity plans based on the results obtained via our original method would more closely match actual damage levels. In addition, microtremor vibration observations were carried out in seven buildings, one of which had no installed non-structural walls because it was under construction at the time, and vibration properties were evaluated based on the results of those observations.

Keywords: Nepal earthquake, Residential building, Damage investigation, Post-earthquake inspection, microtremor

1. Introduction

The Mw 7.9 Nepal Earthquake (also known as the Gorkha Earthquake), which occurred on April 25, 2015, inflicted a lot of injured people in the Kathmandu area and caused numerous buildings, including world heritage sites, to collapse. The authors have studied about the seismic behavior of Japanese super high-rise RC residential building [e.g.,1]. So, in the aftermath of this event, the authors carried out damage investigations for reinforced concrete (RC) high-rise residential buildings from May 31 to June 3, 2015 and microtremor measurements from June 17 to 22, 2015. In our investigation, damage levels, including the damage patterns and natural periods of the affected buildings, were evaluated. This paper reports on the investigation results for the examined buildings. Because the traditional quick post-earthquake inspection of damaged buildings methods focus on only structural damage, the evaluation results don't match reality. In this paper, quick post-earthquake inspection of damaged buildings method, which consider the damage of nonstructural elements, is proposed.

2. Damage investigation outline

Our two investigations were conducted in the nation's capital of Kathmandu Metropolitan City and Lalitpur Sub-Metropolitan City (commonly referred to as Patan). Observations focused on 21 RC residential buildings (Buildings KA-KU) that were over 10 floors high, six of which were under construction when the earthquake struck. In this investigation, visual examination confirmed the most serious failures reported by building residents and listening surveys were conducted to ascertain variations in damage conditions between the main shock and aftershock.

Next, extensive visual examinations of overall building conditions were conducted and residents were interviewed about conditions (e.g., room damage, injured people, resident post-quake movements and repair costs) before and after the earthquake, after which microtremor measurements were conducted in some of the examined buildings.

Figure 1 shows the location of the observed buildings. The designations "KA"-"KU" indicate the buildings examined in this study while "KATNP" designates the Kathmandu American Embassy. Table 1 shows the facades, number of floors, municipal post-earthquake quick inspection results, building investigation status, and microtremor measurement implementation status for each building examined.

Figure 2 shows the time history of the recorded acceleration and pseudo-velocity response spectrum for the main shock and aftershock. The main shock is seen to have a long-period component and a large maximum pseudo-velocity.

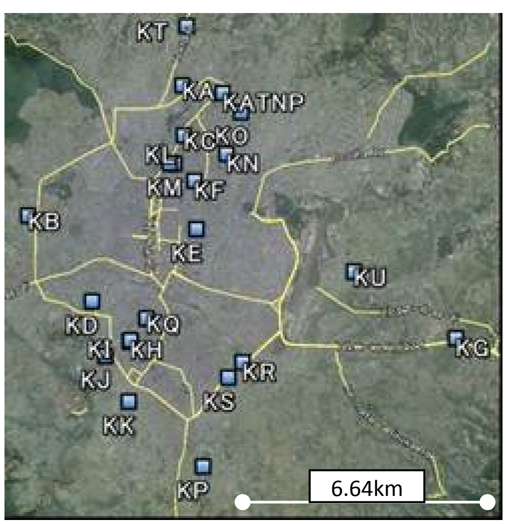
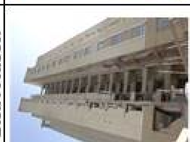
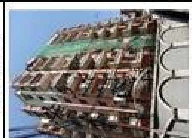
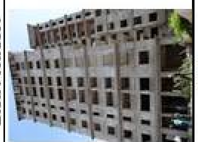
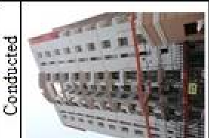
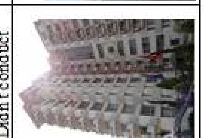
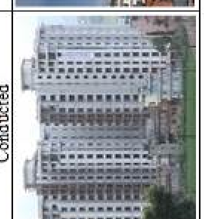
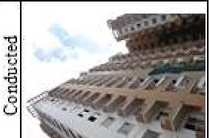
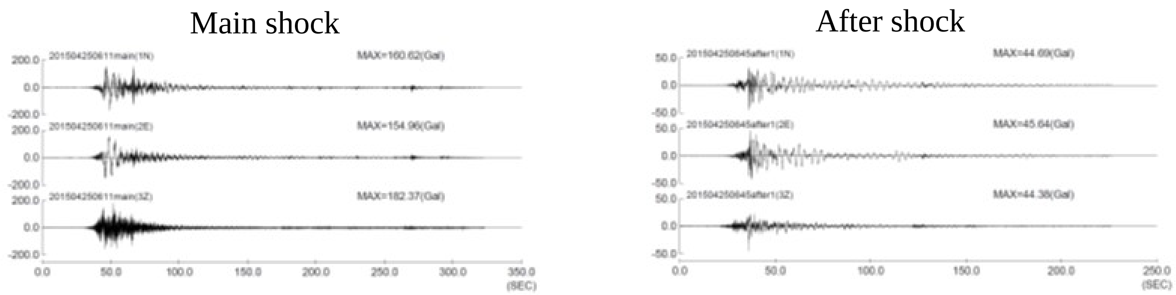


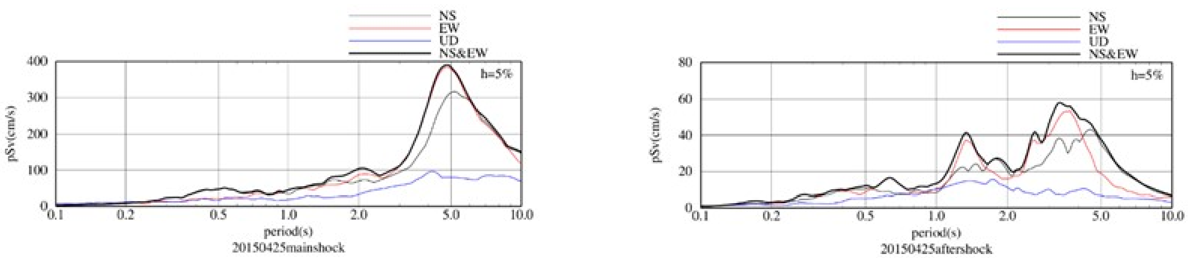
Fig. 1 – Locations of buildings examined

Table 1 – Details of observed buildings

Name	KA	KB	KC	KD	KE	KF	KG
Story	16~17	10~11	13	9	18	13	18
Construction year	2010	2011	Unclear	Unclear	2015	Under construction	Under construction
Post-earthquake quick inspection	RED (Unusable・Unrepairable)	Unclear	Yellow (Repairable)	Yellow (Repairable)	Yellow (Repairable)	Nothing	Nothing
Investigation in the building	Didn't conduct	Didn't conduct	Didn't conduct	Conducted	Conducted	Conducted	Conducted
Microtremor	Didn't conduct	Didn't conduct	Didn't conduct	Conducted	Conducted	Didn't conduct	Didn't conduct
Facade							
Name	KH	KI	KJ	KK	KL	KM	KN
Story	11	15	11~13	16	11	13	12
Construction year	2010	Unclear	2013	2014	Under construction	Unclear	Unclear
Post-earthquake quick inspection	Yellow (Repairable)	Unclear	Yellow (Repairable)	Yellow (Repairable)	Unclear	Yellow (Repairable)	Yellow (Repairable)
Investigation in the building	Didn't conduct	Didn't conduct	Didn't conduct	Conducted	Conducted	Conducted	Didn't conduct
Microtremor	Didn't conduct	Didn't conduct	Didn't conduct	Conducted	Didn't conduct	Didn't conduct	Didn't conduct
Facade							
Name	KO	KP	KQ	KR	KS	KT	KU
Story	15	15	11	12	12	13~18	17
Construction year	2011	Under construction	2013	Unclear	Under construction	2008	2012
Post-earthquake quick inspection	Yellow (Repairable)	Yellow (Repairable)	Yellow (Repairable)	Yellow (Repairable)	Nothing	Yellow (Repairable)	Yellow (Repairable)
Investigation in the building	Conducted	Conducted	Conducted	Conducted	Conducted	Didn't conduct	Didn't conduct
Microtremor	Didn't conduct	Conducted	Conducted	Conducted	Conducted	Didn't conduct	Didn't conduct
Facade							



(a) Time history of recorded acceleration



(b) Pseudo-velocity response spectra

Fig. 2 – Main shock and aftershock

3. Characteristics of RC high-rise residential buildings in Nepal

High-rise residential buildings constructed in and around Kathmandu Metropolitan City are primarily RC frame structures with non-structural infill brick walls (Fig. 3). Although mortar is often used to fill in the joints between the RC frames and brick walls, out-of-plane reinforcements are often not included. The buildings often have complex shapes, as shown in Fig. 4, and many have expansion joints. Most building columns are rectangular in shape (Fig. 5).

Fig. 3 – RC frame with infill brick Wall (KG)

Fig. 4 – Complex building shape (KA, KE)

Fig. 5 – Rectangular shaped columns (KF)

4. Damage summary

4.1 Building damages

In our investigation, little damage was found in structural member. on the other hand significant damage was found in non-structural infill brick walls. Notable damage in the observed buildings included shear failures in brick walls (Fig. 6), cracks along brick joints (Fig. 7), cracks along the joint between bricks and RC frames (Fig. 8), and brick wall collapses (Fig. 9). Gypsum board damage that resulted from ceiling buckling was found in some buildings (Fig. 10). In such cases, the steel furring was often found to be directly attached to the RC frame with nails (Fig. 11).

Fig. 6 – Shear failure in infill brick walls (KM)

Fig. 7 – Cracks along brick joints (KM)

Fig. 8 – Cracks along joints between brick wall and RC frame (KP)

Fig. 9 – Brick wall collapse (KP)

Fig. 10 – Ceiling damage (KD)

Fig. 11 – Joint between steel furring and RC frame (KE)

Damage levels in the lower floors were higher than in the upper floors, which matches the damage breakdown observed in Japanese RC high-rise residential buildings affected by the Great East Japan Earthquake on March 11, 2011 [1]. In addition, damage levels inside the observed building were more severe than damage observed on the building exteriors. Consequently, life continuity plans that were based on structural and exterior building damage did not match actual life continuity requirements.

In Section 3, it was noted that damage and collapse were found in the covers of numerous buildings with expansion joints (Fig. 12). After checking the expansion joint covers in building KD, it was clear they had been connected to the building RC frame using screws (Fig. 13) and that pounding behavior occurred due to the narrow clearance between the joint and the RC building structure (Figs. 14, 15). In addition, there was the movie in which the pounding behavior of Building KD was recorded [e.g. 2].

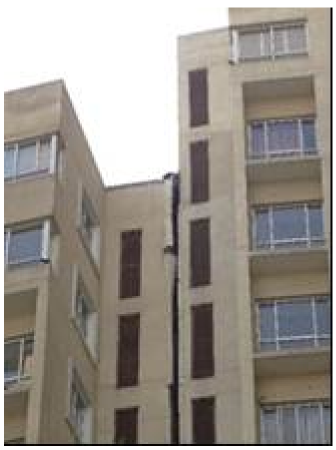


Fig. 12 – Expansion joint damage (KA)

Fig. 13 – Screws connecting the joint cover and RC frame (KD)

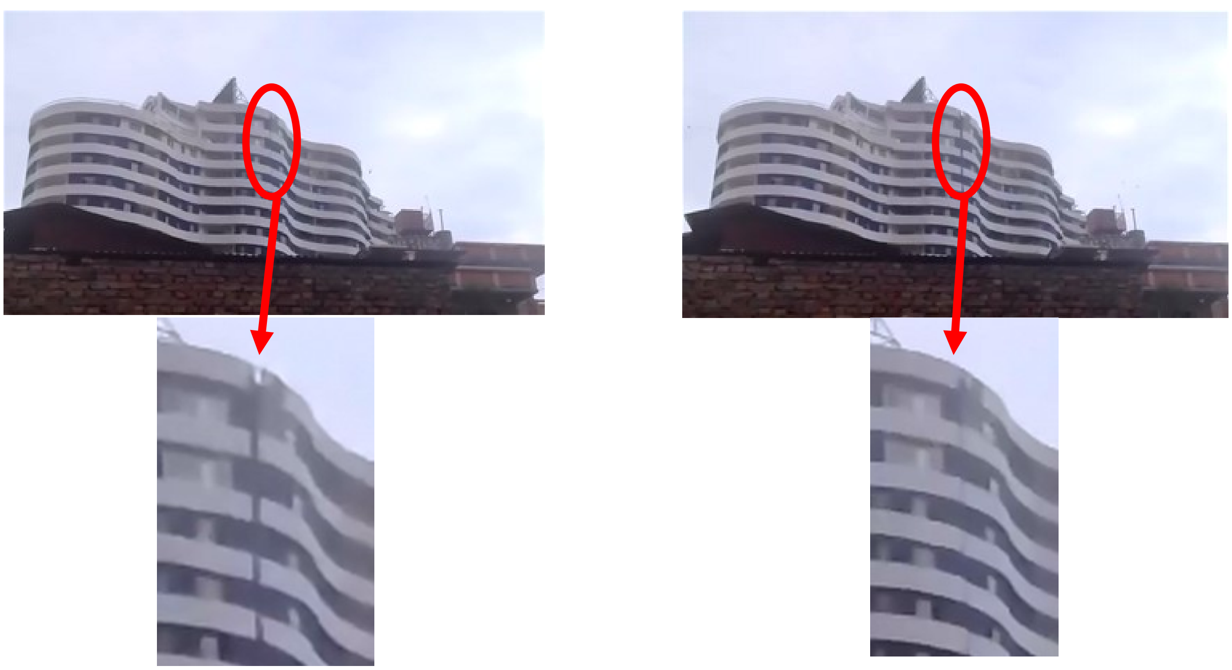


Fig. 14 – Building KE pounding behavior [2]

Fig. 15 – Damaged parapet of Building KE

4.2 Listening survey of residents and interested parties

Results of listening survey of residents in examined buildings are shown below.

Building KA: When the main shock occurred (at AM11 : 56, April 25, 2015), 140 of the total 212 families in residence were in their rooms. After the earthquake, all families were moved out of the building. One person died after behind struck on the head by a falling brick. While this building was initially designed for 11 floors, it is suspected that additional floors were added illegally. Low-rise buildings in the vicinity of Building KA suffered little damage.

Building KD: On the day our investigation was carried out (June 1), seven families resided in the building but all the other families had moved out. In a fourth floor room, some shelves had overturned. Some RC low-rise buildings near Building KD suffered severe damage.

Building KE: When the main shock occurred, 15 families resided in the building. After the earthquake, only one family remained in residence. Nearby buildings suffered little damage.

Building KG: This building was under construction when the earthquake occurred. An administrator who was in the building at the time of the main shock said he did not feel the event.

Building KM: On the day our investigation was carried out (June 2), all residing families had already moved out. This building, which was subdivided into condominium apartments, suffered significant damage due to the aftershock. The building owner will pay the elevator repair cost, but it is currently unclear who will pay for the necessary structural repairs.

Building KO: This building, which was subdivided into condominium apartments, suffered significant damage due to the aftershock.

Examining our survey results, it is clear that numerous residents were forced to move out of their dwellings despite the fact that their building's structural members suffered only minor damage. This is one of the most important problems to be addressed in future disaster prevention and countermeasure planning. On the purely economic side, it was noted that the party or parties responsible for defraying repair costs were often unclear.

5. Quick post-earthquake inspection of damaged buildings

There are a number of methods for conducing quick post-earthquake inspections of damaged buildings (e.g., Ref. 3). However, because many of those methods focus on structural damage, even in cases where structural element damage was minor and non-structural element damage was severe, quick post-earthquake inspection damage results are often underestimated. Accordingly, in this paper, an original method of conducting such inspections of damaged buildings that includes life continuity planning is proposed. Our evaluation standard is shown below.

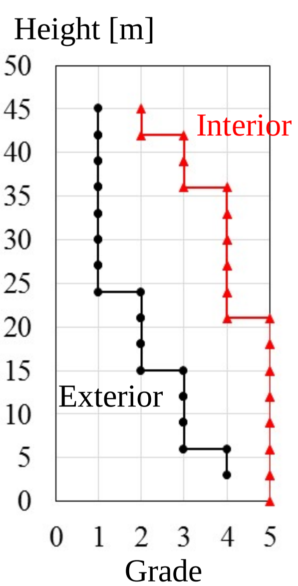
In each floor of every building observed, the degree of damage was estimated. In this study, our quick inspections usually evaluate building damage using facade damage. When interior damage was noted, the inspection results focused on damage directly inside the buildings.

Accordingly, original inspection method, which involves floor-by-floor interior investigations, was applied to some of the buildings. Buildings damage in each floor was evaluated based on Table 2. Damage Grade l indicates no damage. For each floor, the maximum observed damage grade was adopted as the value for that floor. In other words, in a case where a floor has Grade 2, 3, 4, and 5 damage, the damage grade for that floor is Grade 5.

Table 2 – Damage grade list

Damage Grade	Damage to each element
1	No Damage
2	・Paint Damage ・Damage to Joint Between RC Element and Brick Element
3	Minor Shear Failuer of Brick Wall
4	・Serious Shear Failure of Brick Wall ・Collapse of a Part of Brick Wall
5	Collapse of Brick Wall

The results of the building KM damage inspection are shown in Fig. 16. The vertical axis shows the height from ground level to the topmost floor level, while the horizontal axis shows the observed damage grade. In Fig. 17, the black line shows the result based on exterior damage and the red line shows the result based on interior damage. Our original method was able to determine that damage to the lower floors was more severe than upper floor damage, and that damage to the interior of the building was more severe than exterior damage. This indicates that life continuity plans based on our evaluation results (Fig. 16) would match the actual life continuity plans (Fig. 17 and Section 4.2) produced after the event.



(a) Exterior damage

(b) Interior damage (11F)

(c) Interior damage (3F)

Fig. 16 – Results of damage inspection (Building KM)

Fig. 17 – Building KM damage

6. Evaluation of natural period based on microtremor measurements

6.1 Outline of microtremor measurements

In this investigation, microtremor measurements were carried out in seven buildings (KD, KE, KK, KP, KQ, KR, and KS). Building KS was under construction at the time of the earthquake and had an RC frame structure in place but no non-structural elements. Measurements were carried out for buildings fitted with expansion joints. Accelerometers were set at ground level, on the roof, and the first floor level. In buildings where an accelerometer could not be set on the first floor, the meter was set on the second floor.

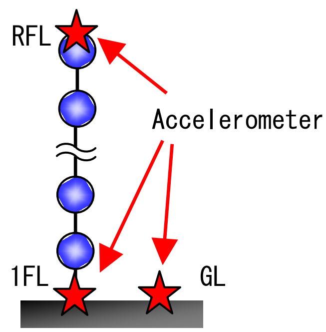


Fig. 18 – Accelerometer positions

6.2 Natural periods for each building

Table 3 shows natural periods for each observed building based on microtremor measurements. These natural periods were estimated by transfer functions that were calculated using the first or second floor level acceleration as input data and the roof level acceleration as output data. The “building height” and “measurement point height” were generally the same as shown in the relevant drawings. If drawings were not available, values are calculated as the floor height (3 m) × number of floors.

Table 3 – Microtremor measurements and natural periods

Name	Story	Height of building (m)	Height of measurement point (m)	Date yyyy/mm/dd	Measurement point	Natural period (s)	
						NS	EW
KD	9	30	30	2015/6/19	GL,1F,RF	0.69	0.64
KE East building				2015/6/20		1.42	1.39
KE Center building	17	50.6	50.6	2015/6/20	GL,1F,RF	1.45	1.41
KE West building				2015/6/20		1.39	1.22
KK South building	15	48	48	2015/6/19	GL,1F,RF	1.08	0.91
KK North building				2015/6/19	GL,1F,RF	1.18	1.13
KP East building	14	45	45	2015/6/19	GL,1F,RF	1.24	1.22
KP West building			42	2015/6/19	GL,2F,RF	1.02	1.01
KQ	11	33	33	2015/6/20	GL,1F,RF	0.67	0.78
KR	13	39	39	2015/6/20	1F,RF	1.17	1.33
KS	13	39	36	2015/6/20	2F,RF	0.80	1.05

Figure 19 shows the relationship between the natural period for the north-south (NS) and east-west (EW) directions, while Fig. 20 shows the relationship between the natural period for the NS direction and the measurement point height. In these figures, linear approximate equations that are evaluated by the least-square method (LSM) and coefficient of determinations (R^2) are also shown.

From Fig. 19, it can be seen that the natural periods for the NS and EW directions are almost the same. Even though these buildings were damaged, this result indicates that they have similar stiffness levels in each direction.

This result also suggests that complex shapes do not affect the building vibrational properties. Additionally, Fig. 20 shows that the natural period is linearly related to the measurement point height, with a proportionality factor of 0.025. Though the period may be linearly related to the building height, it is not clear. Because there are two cases that the meter was set on the second floor (KP and KS). While this detail is shown below, this factor is smaller than that for India's "Criteria for Earthquake Resistant Design of Structures" (hereafter Indian Standard).

In Fig. 21, the observed natural periods for each building (T_{1obsNS} and T_{1obsEW}) are compared with those calculated using Indian Standard using the expression $T_{1IS} = 0.075h^{0.75}$, where h is the building height. From this figure, it is clear that T_{1obs} / T_{1IS} is less than 1.0 in many cases. Considering that T_{1obs} includes damage effects, this result indicates that T_{1obs} failed to match the Indian Standard.

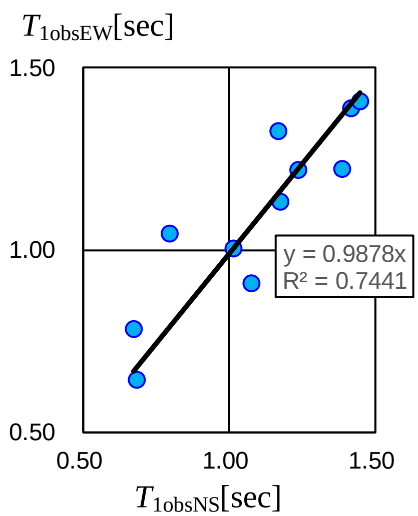


Fig. 19 – Relationship between T_{1obsNS} and T_{1obsEW}

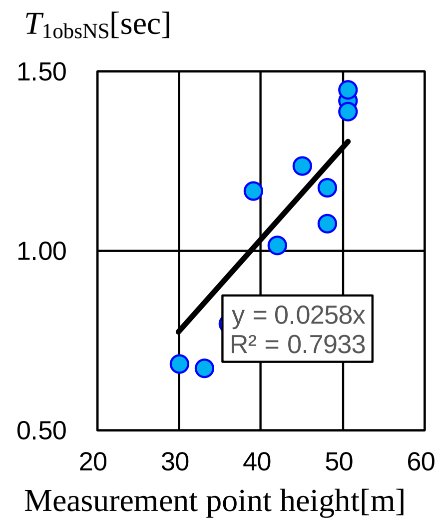


Fig. 20 – Relationship between T_{1obsNS} and measurement point height

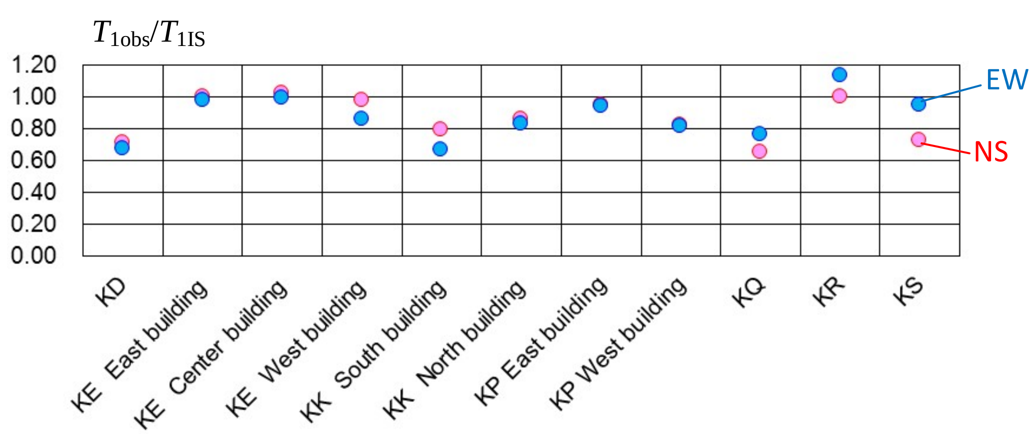


Fig. 21 – Comparison of T_{1obs} and T_{1IS}

7. Conclusions

Damage sustained by RC high-rise residential buildings during the 2015 Nepal earthquake were investigated, including interior and non-structural damage. The findings of this paper are summarized as follows:

(1) Structural elements suffered little damage. On the other hand, non-structural elements (e.g., brick walls) often sustained severe damage.

(2) Lower floor damage levels were more severe than upper floor levels. (Max about 4 times in KM (Fig.16))

(3) Interior damage was more severe than exterior damage. (Max about 4 times in KM (Fig.16))

(4) Because expansion joint clearances were narrow, pounding evidence was found. Collapses and expansion joint cover damage were also found in these buildings.

(5) An original method for conducting quick post-earthquake inspections for damaged buildings was proposed. The results indicate that this method can provide the basis for more realistic life continuity plans and actual damage evaluations.

(6) Natural periods were evaluated based on microtremor measurements. The relationship between T_{1obs} (observed natural period) vs. measurement point height (T_{1obs}=0.025×measurement point height) and T_{1IS} (natural period based on the Indian Standard) was examined. The results suggest that T_{1obs} failed to match the Indian Standard (Maximum percentage error is about 35% and average percentage error is about 15%. (Fig.21)).

8. Acknowledgements

We would like to thank Mr. Prakash Poudel, as well as the residents and interested parties of each building, for their invaluable help and support.

9. References

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