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Seismic Performance of Vertical Irregular Steel FrameStructure under Mainshock-Aftershock

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Abstract: ***The majority of the structures are involved with architectural importance and it is highly impossible to achieve uniform structural properties in all directions. Hence earthquake resistant design codes considered it as irregular frames based on relative difference in the story properties. In many cases these irregularities are responsible for structural collapse of buildings under earthquake ground motions. The seismic response of buildings with irregular distribution of stiffness along the height may be differentfrom that of regular building. Also, past earthquakes showed that structure may be subjected to sequence of ground motions but current codes do not have guidelines for such cases. It is considered that aftershock do not cause any more damage to damaged structure by the preceding mainshock ground motion. In this study steel moment resisting frame buildings are evaluated to understand the seismic response of vertical stiffness irregular frames subjected to mainshock-aftershock ground motions. The 9-story steel moment resisting frame building situated in Los Angeles is used in this study was originally developed as part of the SAC steel project. In this study soft and stiff storey case was considered at three different locations along the height, i.e., at bottom storey, mid-height storey and top storey. The single modification factor is used for irregularity. For comparison purpose dynamic properties of regular and irregular frames are kept same. Two sets of 6 records were selected representing a seismic hazard level of 2% and 10% probability of exceedance in 50 years respectively as mainshock. Two sets of 30 mainshock-aftershock ground motion are considered for the study. These ground motions were developed using randomized approach. A non-linear time history analysis of regular and irregular building is carried out separately under mainshock and mainshock-aftershock. The effect of building irregularity was studied for single storey modification at bottom storey, mid-storey and top storey with comparison to regular building. The comparison of a regular and irregular building is carried out in terms of maximum roof displacement and interstorey drift ratio. Also, comparison of frames under mainshock and mainshock-aftershock is done.***
Keywords: Seismic performance, Vertical irregularity, Steel frame structure, Mainshock-aftershock, Structural behavior, Vulnerability, Failure modes, Retrofit strategies, Seismic design, Resilience, Earthquake engineering, Seismic analysis.

I. INTRODUCTION

As per literature review many researchers has shown interest in the area of study of vertically irregular buildings and their seismic behavior under earthquake ground motion. Despite some anticipated differences due to the different approaches used, all research efforts reached relatively compatible conclusions. Still, in all cases several issues were left open. The past research show that the seismic behavior of vertically irregular buildings can be significantly different in comparison to the regular structure. And also, all studies focused on effect of irregularity under single ground motions rather than series of earthquake. But in earthquake proneregion are structure may exposed to series of earthquake. The chapter is divided into two subsections namely mainshock- aftershock and structural irregularity.

II. PROBLEM STATEMENT

1) Vertical irregularities in steel frame structures, such as changes in column heights or stiffness, can lead to complexseismic responses and potential failure modes.
2) Mainshock-aftershock sequences, which are common in earthquake-prone regions, can result in additional damage toalready weakened structures and increase the risk of collapse.
3) Despite the importance of understanding the seismic performance of vertical irregular steel frame structures undermainshock-aftershock, there is currently limited research in this area.
4) There is a need to investigate the behavior and potential failure modes of these structures under mainshock-aftershock,and to evaluate retrofit strategies to improve their seismic performance and resilience.

5) The outcomes of this research could have significant implications for building codes and standards, as well as for thesafety of individuals living and working in these structures in earthquake-prone regions.

III. AIM

The aim of studying the seismic performance of a vertical irregular steel frame structure under mainshock-aftershock is to evaluatethe structural behavior and potential damage of the building during a seismic event. The study should aim to:

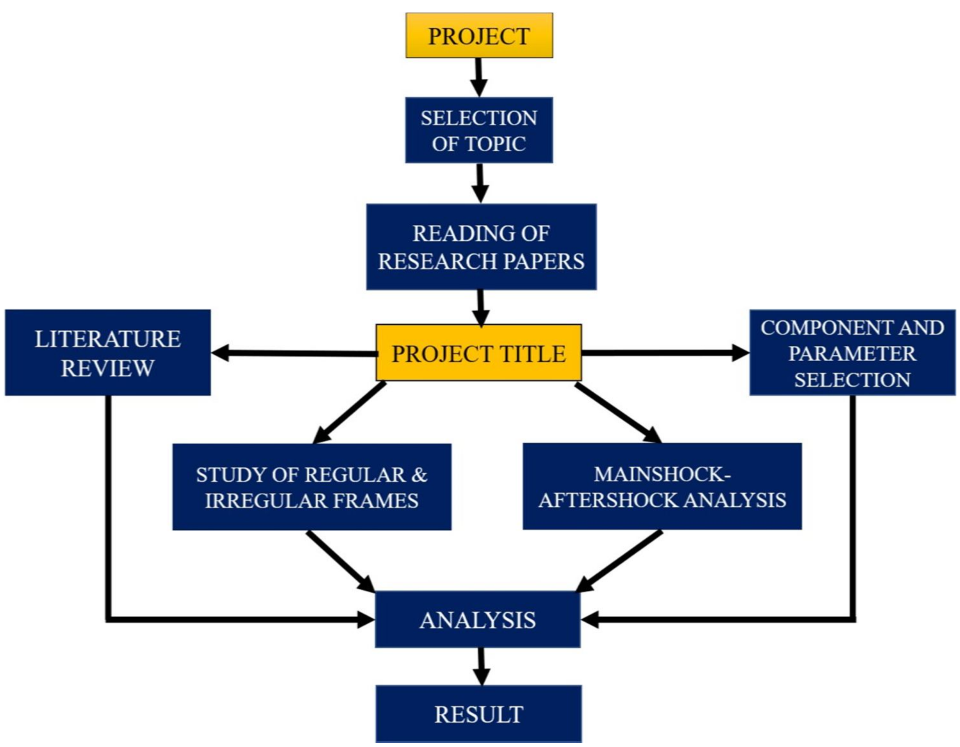
1) Investigate the effects of mainshock-aftershock sequences on the performance of the structure, including its response,dynamic characteristics, and stability.
2) Identify the vulnerability and failure modes of the structure under different levels of seismic activity, including the impact of vertical irregularities.
3) Propose and evaluate retrofit strategies to enhance the seismic performance of the structure and reduce the risk of damage or collapse.
4) Develop recommendations for building codes and standards to improve the seismic design of vertical irregular steel frame structures and enhance their resilience to seismic hazards.

Overall, the aim is to contribute to a better understanding of the seismic behavior of vertical irregular steel frame structures under mainshock-aftershock sequences and to provide guidance for improving their seismic performance and resilience.

IV. OBJECTIVES

1) To evaluate the dynamic response of the vertical irregular steel frame structure under mainshock-aftershock sequences, considering the impact of vertical irregularities on its seismic behavior.
2) To analyze the structural vulnerability and failure modes of the building under different levels of seismic activity, including the impact of vertical irregularities.
3) To propose and evaluate retrofit strategies to enhance the seismic performance of the structure and reduce the risk ofdamage or collapse.
4) To develop recommendations for building codes and standards to improve the seismic design of vertical irregular steelframe structures and enhance their resilience to seismic hazards, based on the findings of the study.

V. METHODOLOGY



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1) *Literature Review:* Conduct a comprehensive literature review to identify relevant research studies, codes, standards, and guidelines related to the seismic design and performance of steel frame structures.
2) *Ground Motion Selection:* Select appropriate ground motion records for the mainshock and aftershock based on thesite-specific hazard analysis and design earthquake parameters.
3) *Analysis:* Perform nonlinear dynamic time history analysis of the structure under the selected ground motion records.
4) Results and Performance Evaluation: Evaluate the seismic performance of the structure based on the analysis results.
5) *Retrofit Strategies:* Propose and evaluate retrofit strategies to enhance the seismic performance of the structure andreduce the risk of damage or collapse.
6) *Conclusions and Recommendations:* Summarize the main findings of the study and provide recommendations for future research, building codes, and standards.

VI. WORK DONE

A. *Siesmic Responses Of Smrf Under Mainshock*

1) *Regular Building Frame*

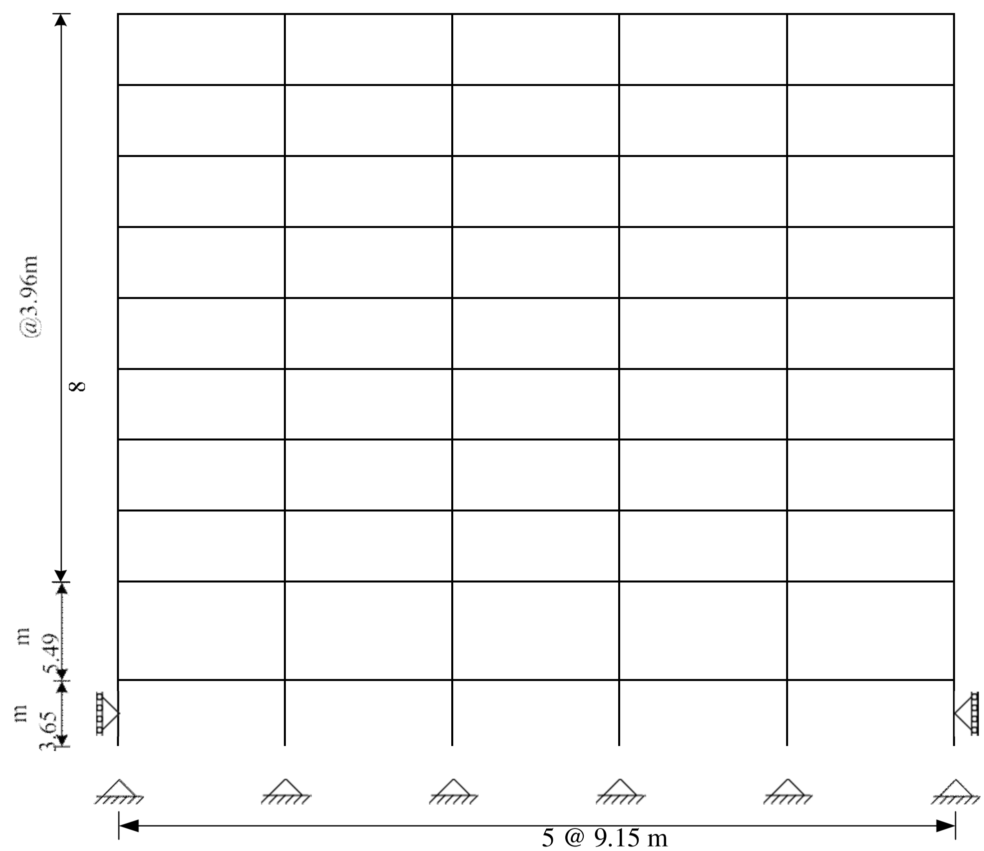

Fig.1 Elevation of 9 storey steel building

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2) Irregular Building Frame

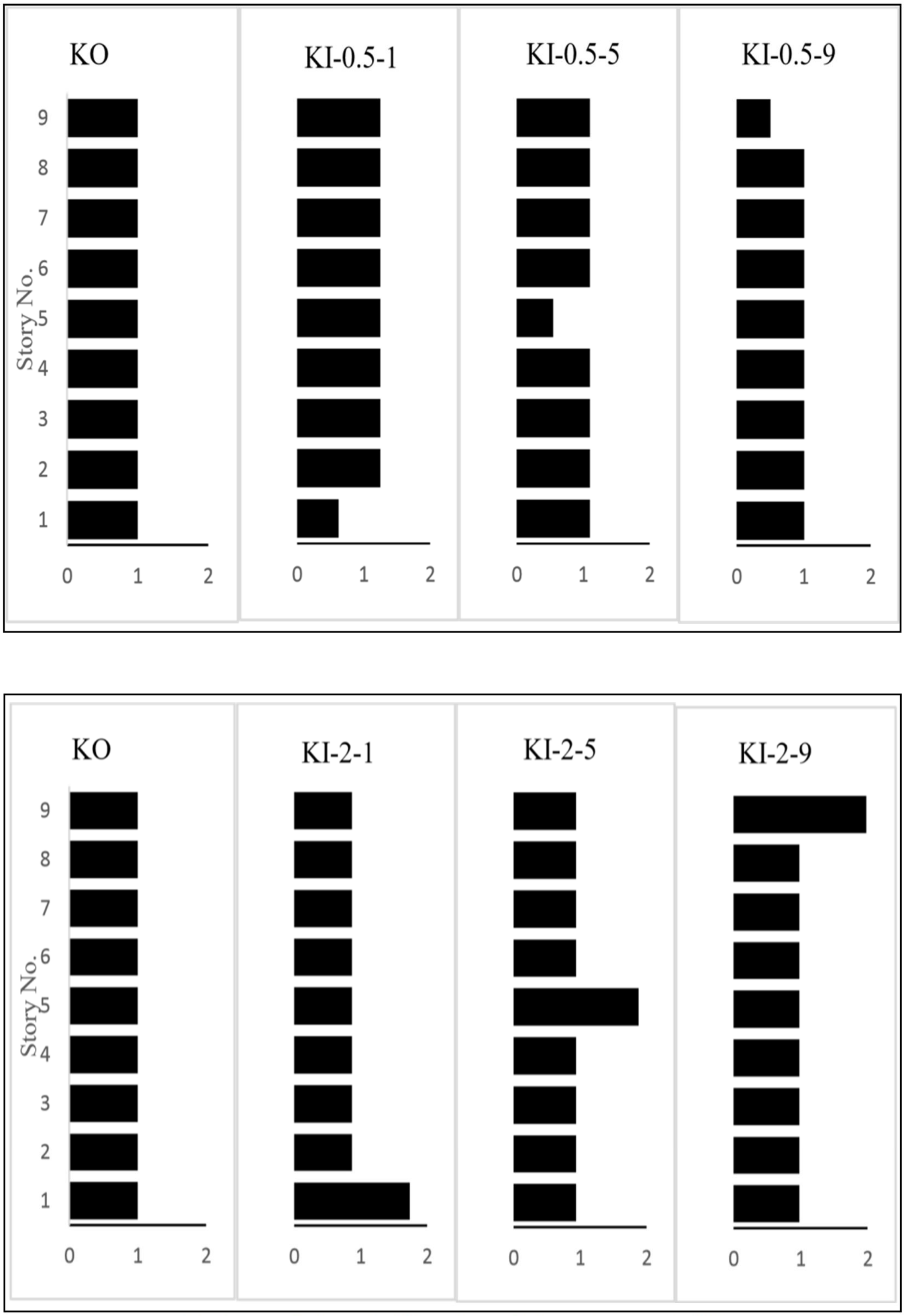

Fig.2 : Description of stiffness irregularity of 9 storey building

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3) Non-linear Static Pushover Analysis

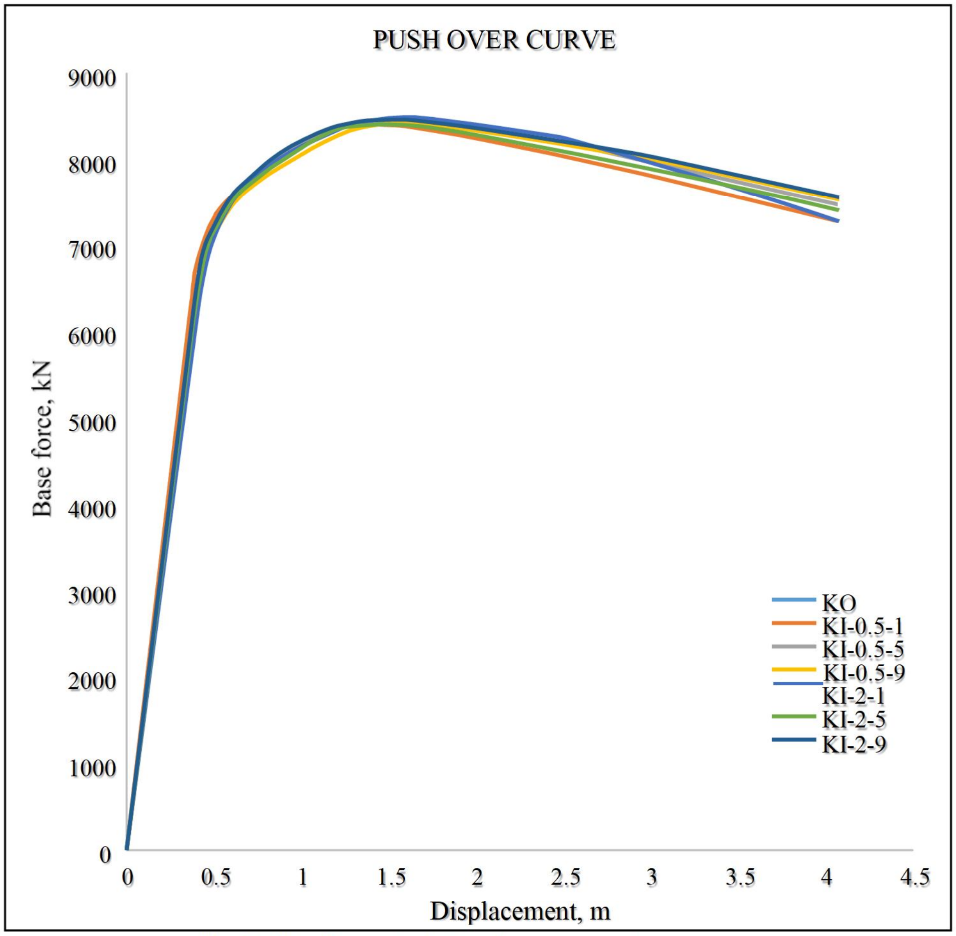

Fig.3 : Nonlinear static (pushover) capacity curve

4) Ground Motions

Table:1 Characteristics of Los Angeles ground motion records(Somerville et al. 1997)

Designation	Record information	Duration (s)	Magnitude	PGA (g)
10/50 set of records (475 years return period)				
LA15	1994, Northridge	14.95	6.7	0.533
LA16	1994, Northridge	14.95	6.7	0.579
LA17	1994, Northridge	59.98	6.7	0.569
LA18	1994, Northridge	59.98	6.7	0.817
LA19	1986, North palm spring	59.98	6.0	1.019
LA20	1986, North palm spring	59.98	6.0	0.986
2/50 set of records (2475 years return period)				
LA21	1995, Kobe	59.98	6.9	1.282
LA22	1995, Kobe	59.98	6.9	0.919
LA23	1989, Loma Prieta	24.99	7.0	0.416
LA25	1994, Northridge	14.95	6.7	0.867
LA26	1994, Northridge	14.95	6.7	0.942
LA27	1994, Northridge	59.98	6.7	0.925

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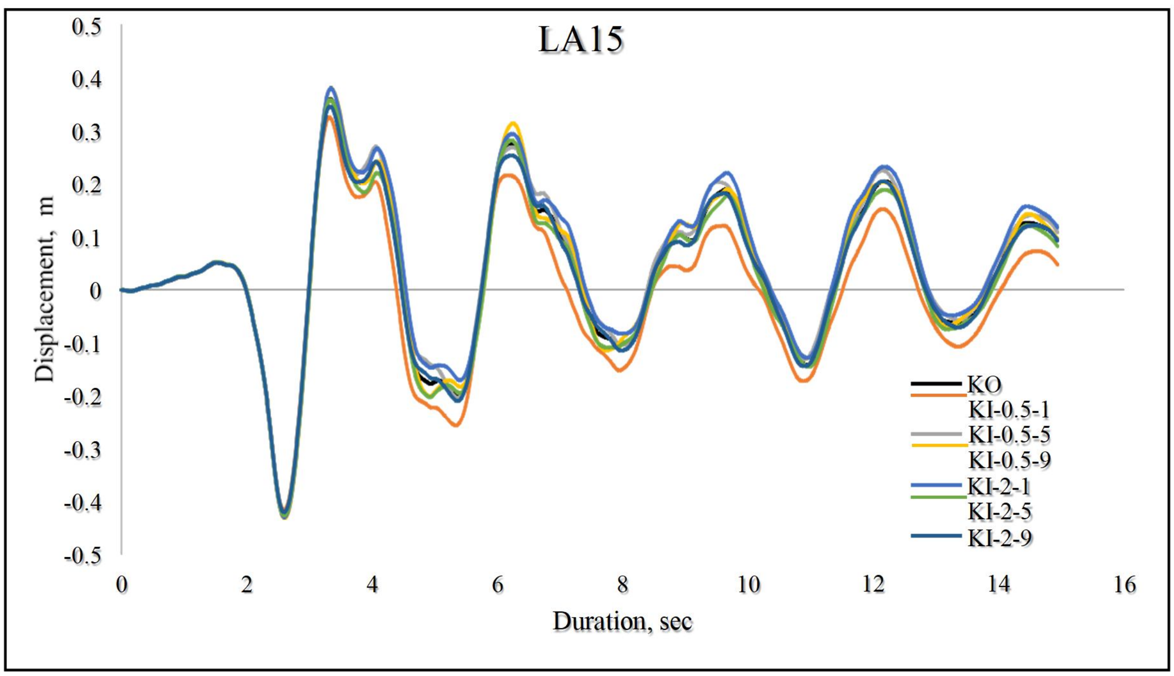
5) Comparison of regular and irregular building frame subjected to mainshock

a) Maximum Roof Displacement

Table:2 Roof displacement of regular and irregular frame under mainshock

GM	KO	KI-0.5-1	KI-0.5-5	KI-0.5-9	KI-2-1	KI-2-5	KI-2-9
	10/50 set of records						
LA15	425.1	415.48	422.58	431.77	429.43	426.39	420.19
LA16	699.3	686.01	707.83	696.39	701.76	687.73	702
LA17	644	591.75	632.13	666.11	675.72	640.09	627.7
LA18	581.33	555.61	552.16	607.94	598.99	604.19	560.47
LA19	251	226.2	148.86	269.73	212.8	255.1	237.5
LA20	509.5	503.24	507.62	513.03	512.92	510.54	507.28
	02/50 set of records						
LA21	613.8	580.22	632.52	653.03	640	637.96	605.42
LA22	874.6	850.29	908.43	869.3	873.56	845.7	884.69
LA23	596.9	574.51	599.29	611.27	606.17	593.21	584.99
LA25	690.9	674.91	686.69	701.88	698.09	692.85	682.78
LA26	928.9	898.83	935.92	920.88	939.45	920.66	933
LA27	791	748.82	801.69	812.4	817.47	780.91	780.17



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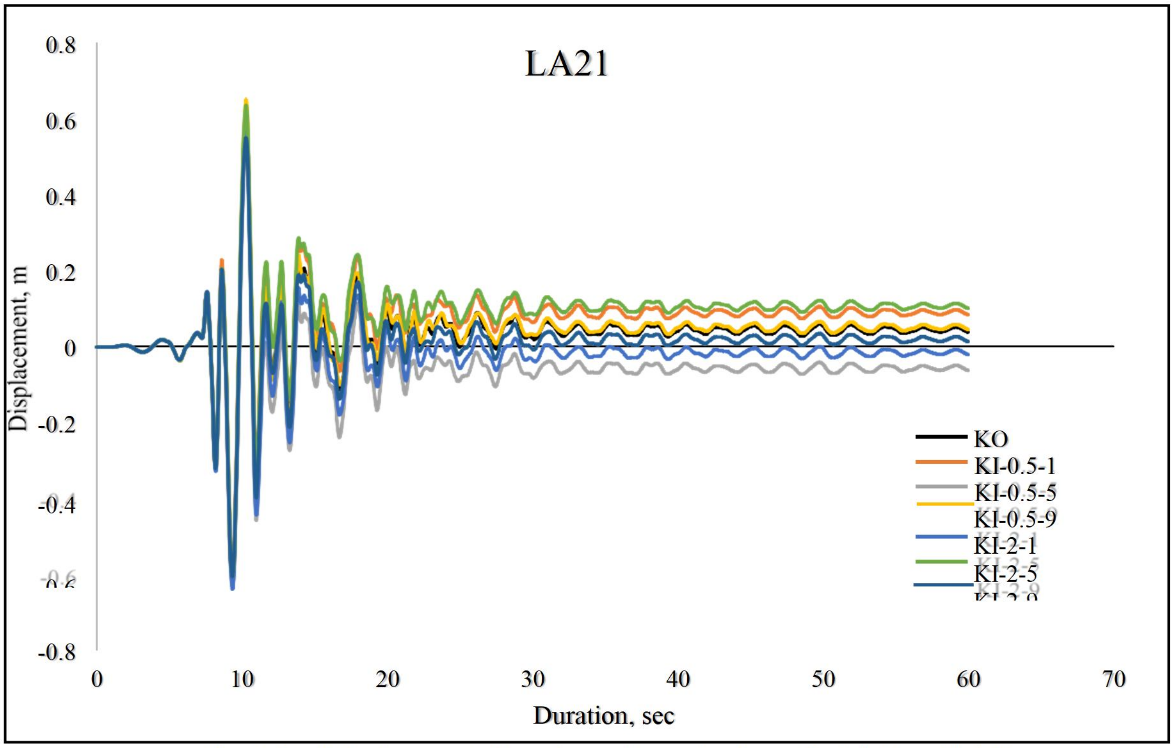


Fig.4: Roof displacement of regular and irregular frame for LA15 and LA21

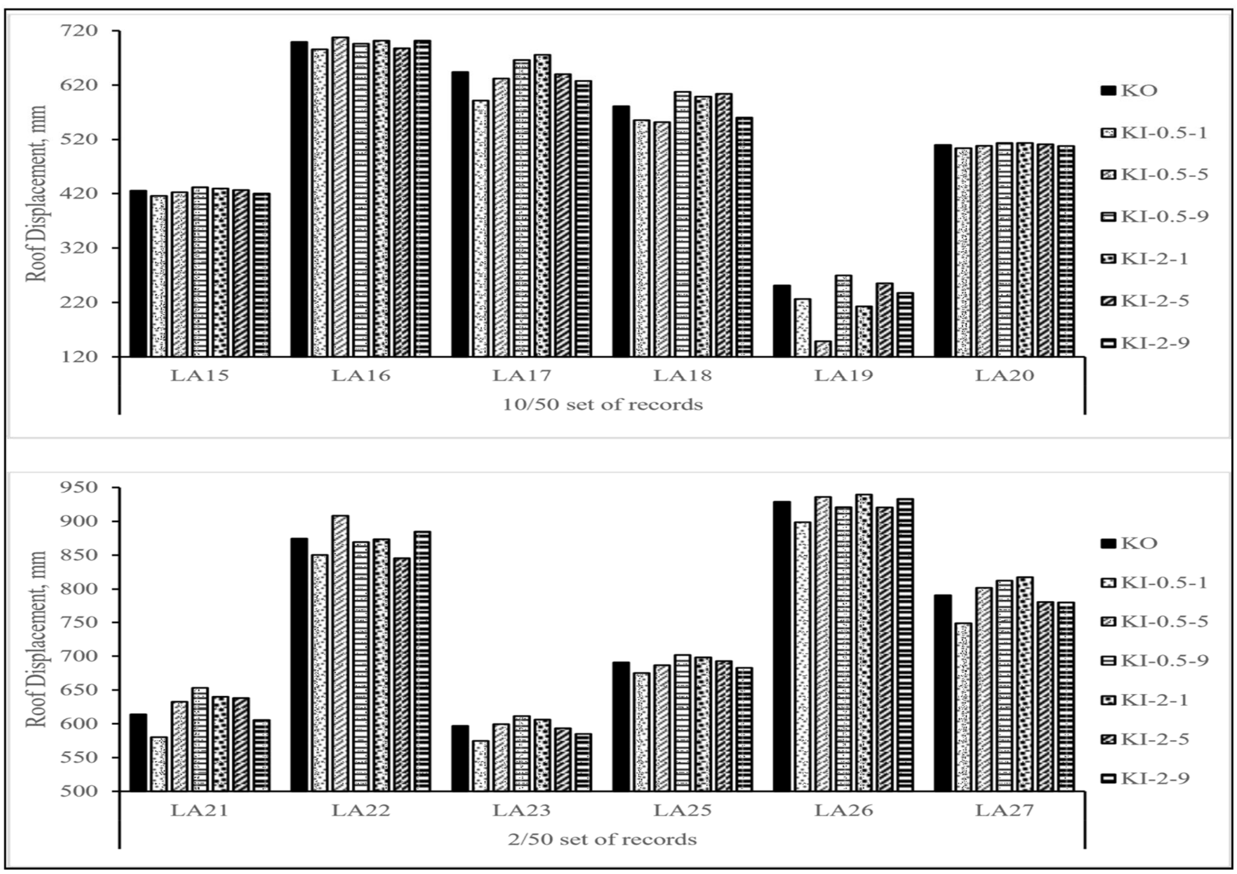
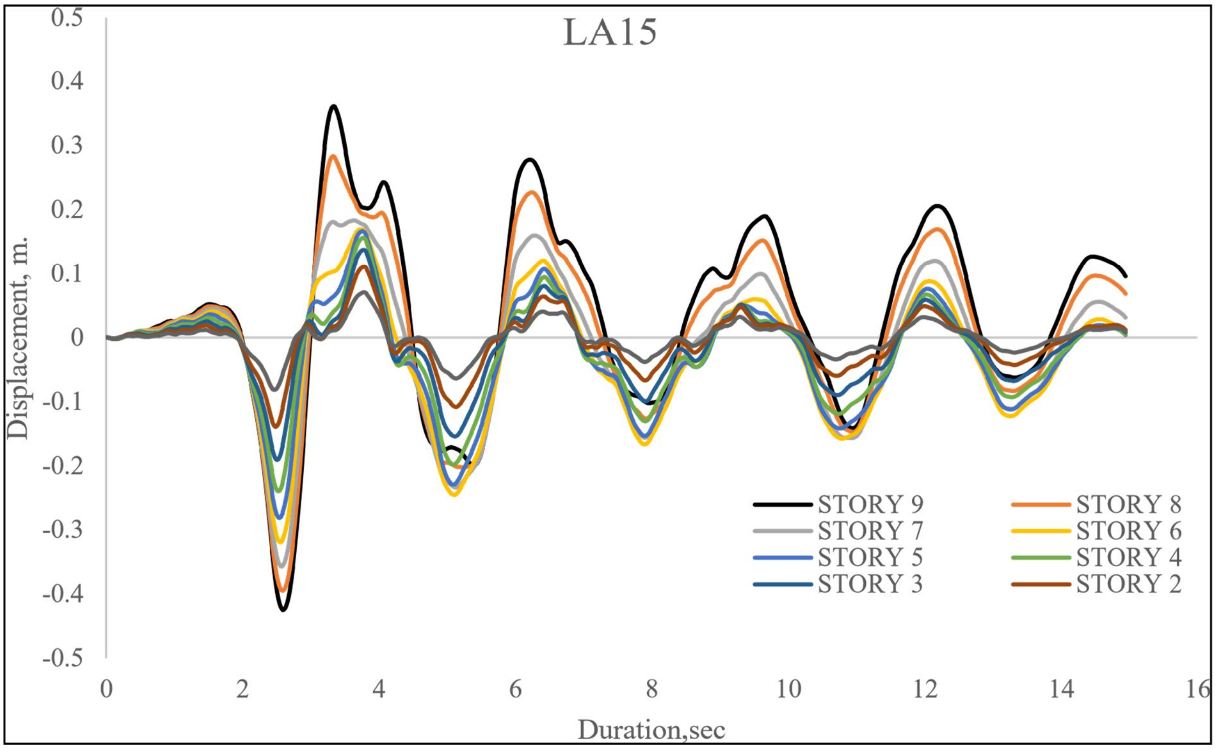


Fig.5 : Maximum Roof displacement of regular and irregular frame under MS



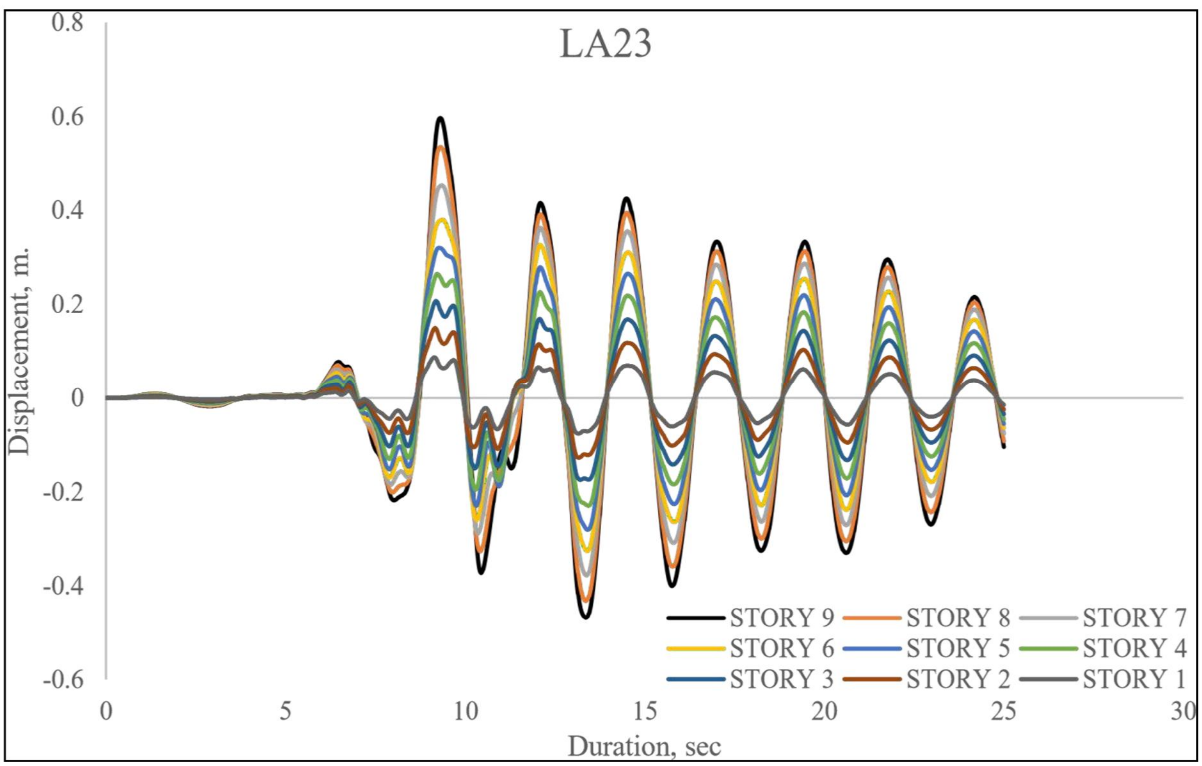


Fig.6 : Storey displacement of regular and irregular frame under LA15 and LA23

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6) Inter-storey Drift Ratio

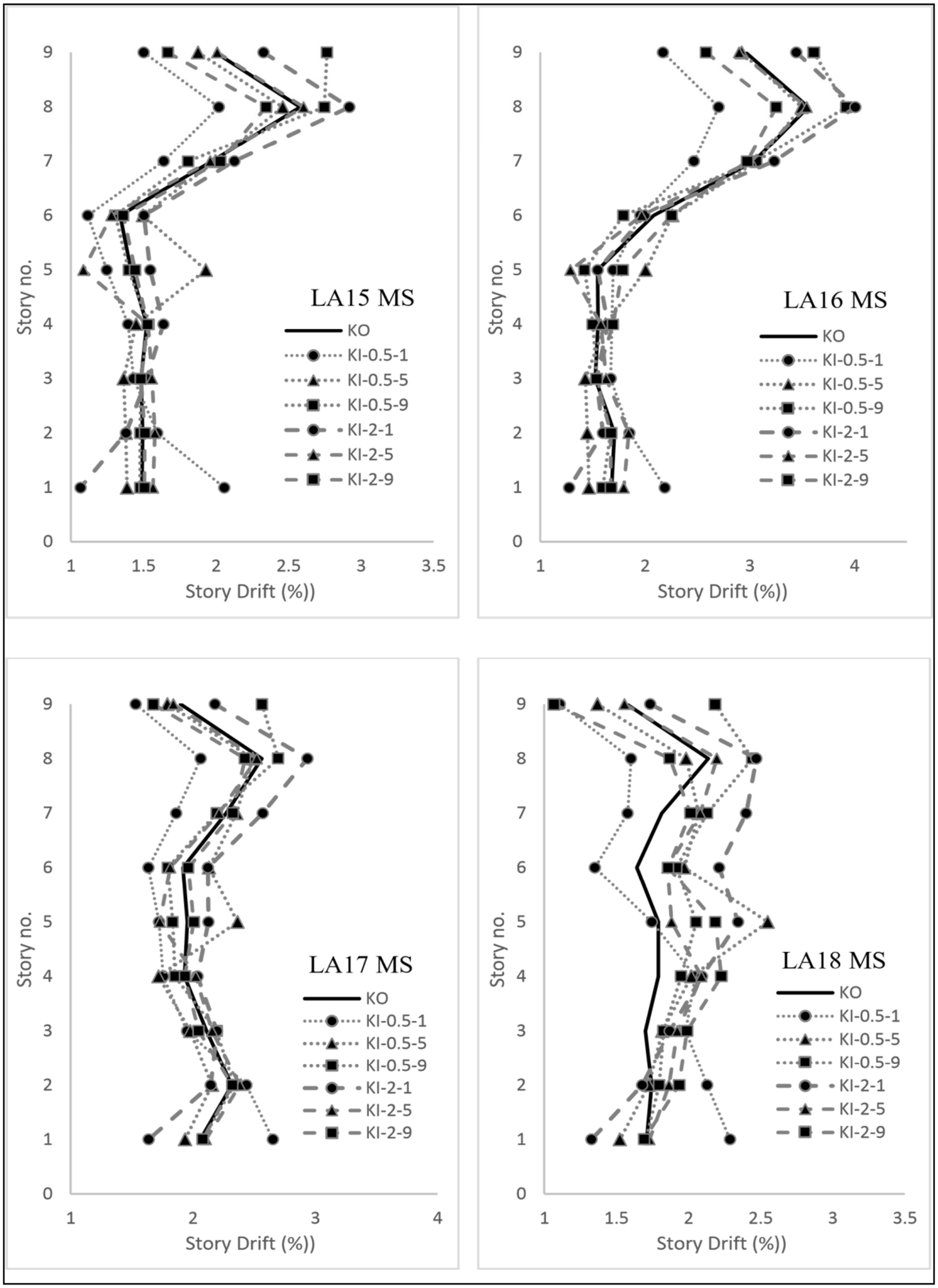

Fig.7 : Interstorey drift ratio of regular and irregular frame structures under mainshock LA15, LA16, LA17 and LA18

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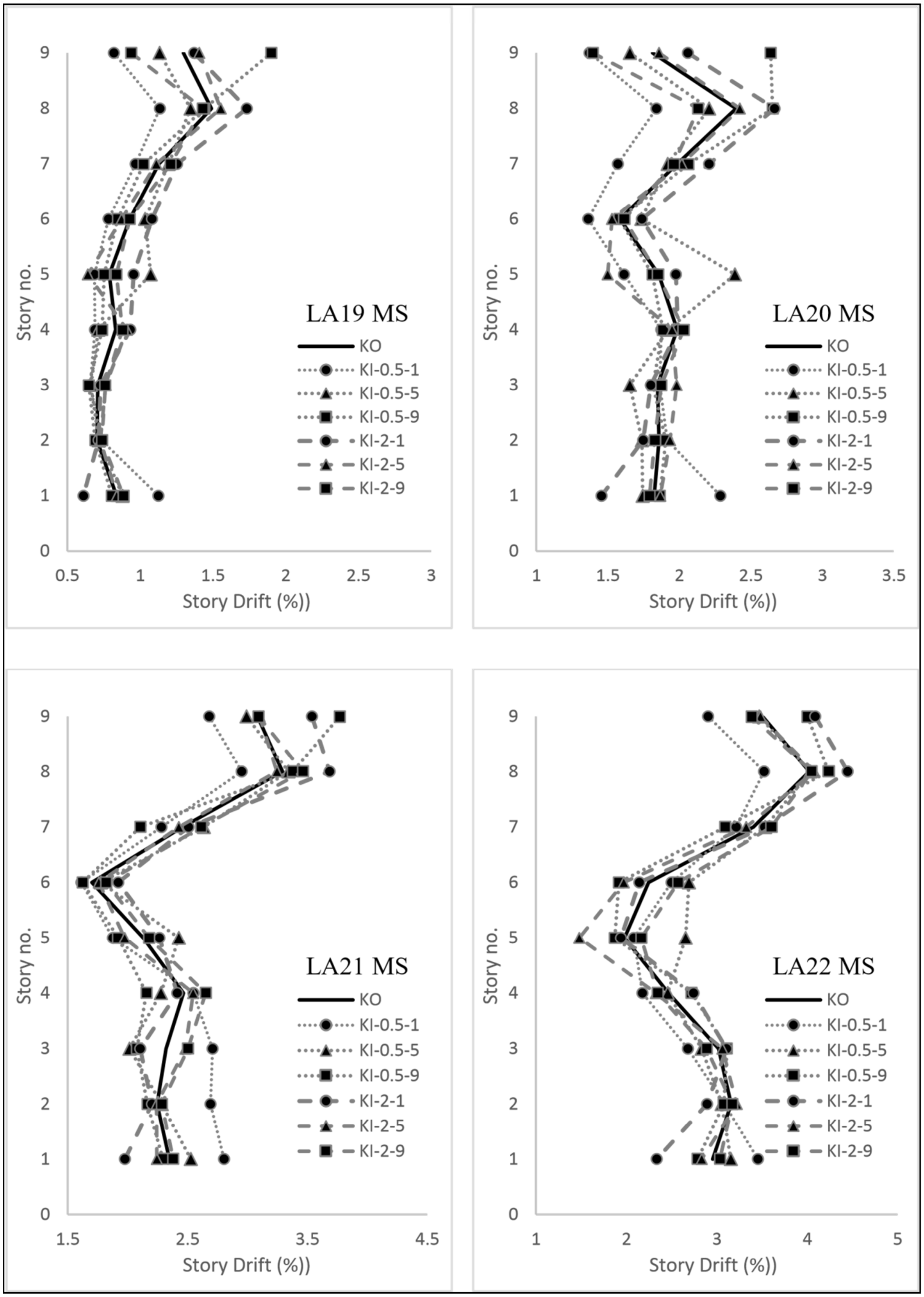

Fig.8 : Interstorey drift ratio of regular and irregular frame structures under mainshock LA19, LA20, LA21 and LA22

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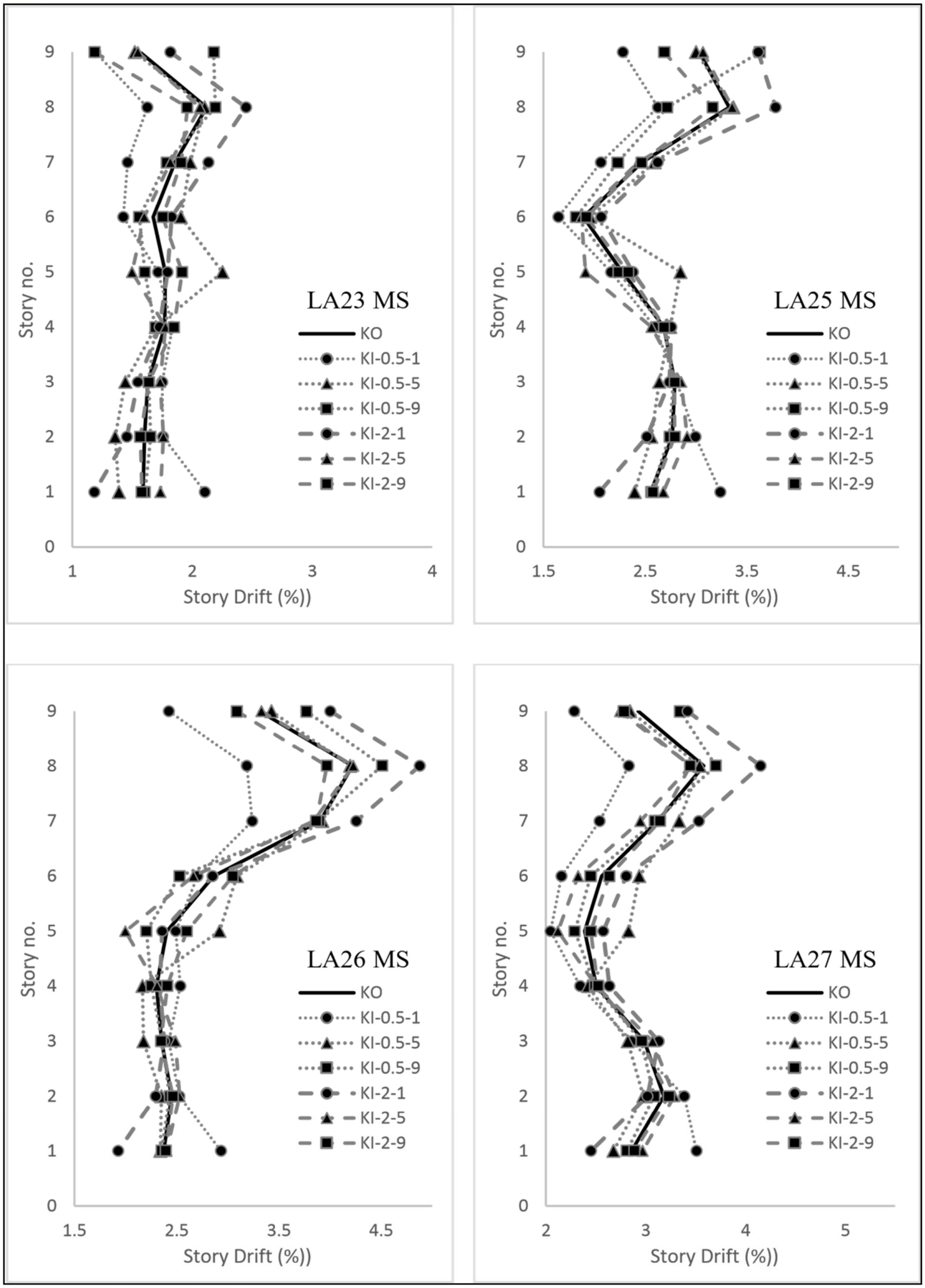

Fig.9 : Interstorey drift ratio of regular and irregular frame structures under mainshock LA23, LA25, LA26 and LA27

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B. Seismic Responses Of Smrf Under Mainshock-Aftershock

1) Development of mainshock-aftershock sequential ground motions

Table 3 Comparison of mainshocks and aftershocks (Mm −Ma=0.2)

	Mainshock		Aftershock		
EQ records	Seismic hazard	λ Mm	λ Ma	Seismic hazard	Scale factor
LA15 – LA20	10%/50yr	0.00211	0.00356	15%/50yr	0.90
LA21 – LA27	2%/50yr	0.000404	0.000683	3%/50yr	0.91

Table 4 Combinations of mainshocks and aftershocks

GM	10%/50yr						2%/50yr					
MS	LA15	LA16	LA17	LA18	LA19	LA20	LA21	LA22	LA23	LA25	LA26	LA27
AS	LA16	LA15	LA15	LA15	LA15	LA15	LA22	LA21	LA21	LA21	LA21	LA21
	LA17	LA17	LA16	LA16	LA16	LA16	LA23	LA23	LA22	LA22	LA22	LA22
	LA18	LA18	LA18	LA17	LA17	LA17	LA25	LA25	LA25	LA23	LA23	LA23
	LA19	LA19	LA19	LA19	LA18	LA18	LA26	LA26	LA26	LA26	LA25	LA25
	LA20	LA20	LA20	LA20	LA20	LA19	LA27	LA27	LA27	LA27	LA27	LA26

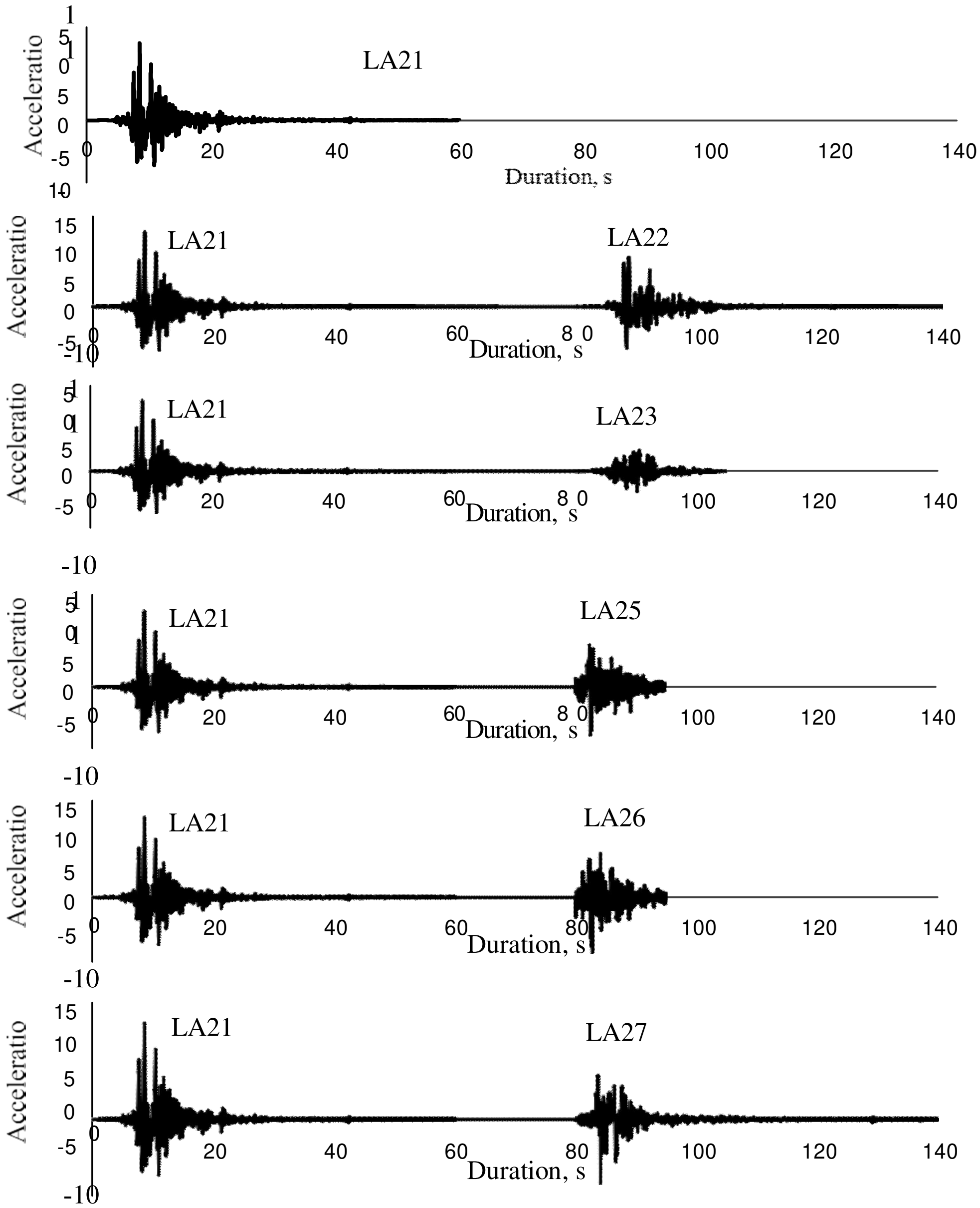

Fig.10: Mainshock-Aftershock ground motion for LA21

2) Comparison of regular and irregular building frame subjected to mainshock-aftershock

a) Maximum Roof Displacement

Table (a) Roof displacement of regular and irregular frame under LA15 MS-AS

		Ko	Ki-0.5-1	Ki-0.5-5	Ki-0.5-9	Ki-2-1	Ki-2-5	Ki-2-9
Ms	La15	425.1	415.48	422.58	431.77	429.43	426.39	420.19
Ms-as	15.16	632.62	587.94	646.8	639.72	649.45	622.35	640.05
	15.17	668.66	593.7	670.27	693.03	703.4	654.72	652.46
	15.18	583.86	533.54	570.31	610.78	612.72	595.63	573.75
	15.19	425.12	415.48	422.56	431.78	429.44	426.41	420.16
	15.20	475.88	462.58	487.14	496.67	495.05	467.54	488.02

Table (b) Roof displacement of regular and irregular frame under LA16 MS-AS

		KO	KI-0.5-1	KI-0.5-5	KI-0.5-9	KI-2-1	KI-2-5	KI-2-9
MS	LA16	699.3	686.01	707.83	696.39	701.76	687.73	702
MS-AS	16.15	699.26	685.45	707.08	696.24	701.81	687.77	701.7
	16.17	727.85	688.46	728.26	724.06	739.02	719.54	730.52
	16.18	699.26	685.45	707.08	696.24	701.81	687.77	701.7
	16.19	699.26	685.45	707.08	696.24	701.81	687.77	701.7
	16.20	699.26	685.45	707.08	696.24	701.81	687.77	701.7

Table (c) Roof displacement of regular and irregular frame under LA17 MS-AS

		KO	KI-0.5-1	KI-0.5-5	KI-0.5-9	KI-2-1	KI-2-5	KI-2-9
MS	LA17	644	591.75	632.13	666.11	675.72	640.09	627.7
MS-AS	17.15	643.99	591.45	631.42	667.86	676.59	640.3	626.96
	17.16	690.11	680.64	680.35	689.55	691.37	689.28	699.68
	17.18	643.96	620.17	631.57	666.87	675.92	644.08	627.25
	17.19	643.96	591.39	631.57	666.87	675.92	640.49	627.25
	17.20	643.96	591.39	631.57	666.87	675.92	640.49	627.25

Table (d) Roof displacement of regular and irregular frame under LA18 MS-AS

		KO	KI-0.5-1	KI-0.5-5	KI-0.5-9	KI-2-1	KI-2-5	KI-2-9
MS	LA18	581.33	555.61	552.16	607.94	598.99	604.19	560.47
MS-AS	18.15	581.33	555.69	552.16	607.94	598.99	604.19	560.47
	18.16	654.45	643.45	646.75	679.67	672.63	653.14	647.98
	18.17	646.48	600.91	637.52	687.09	682.55	649.52	613.07
	18.19	584.38	558.54	555.39	610.84	602.59	606.89	563.75
	18.20	584.38	558.54	555.39	610.84	602.59	606.89	563.75

Table (e) Roof displacement of regular and irregular frame under LA19 MS-AS

		KO	KI-0.5-1	KI-0.5-5	KI-0.5-9	KI-2-1	KI-2-5	KI-2-9
MS	LA19	251	226.2	148.86	269.73	212.8	255.1	237.5
MS-AS	19.15	391.18	376.25	387.4	396.86	397.22	392.2	381.5
	19.12	641.15	624.23	646.8	642.46	637.52	631.85	640.21
	19.17	615.33	570.4	611.68	641.69	642.03	612.65	599.7
	19.18	568.3	549.6	540.39	594.24	583.66	588.45	550.29
	19.20	468.6	555.1	471.18	494.8	479.33	469.32	463.81

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Table (f) Roof displacement of regular and irregular frame under LA17 MS-AS

		KO	KI-0.5-1	KI-0.5-5	KI-0.5-9	KI-2-1	KI-2-5	KI-2-9
MS	LA20	509.5	503.24	507.62	513.03	512.92	510.54	507.28
MS-AS	20.15	510.76	504.09	508.52	513.79	513.95	511.71	508.29
	20.16	660.54	636.87	669	662.43	647.37	637.89	674.36
	20.17	664.3	602.7	646.63	693.67	692.35	655.19	648.74
	20.18	595.1	569.3	568.93	626.11	595.45	600.38	595.4
	20.19	509.5	503.2	507.65	512.96	512.92	510.56	507.25

Table (g) Roof displacement of regular and irregular frame under LA21 MS-AS

		KO	KI-0.5-1	KI-0.5-5	KI-0.5-9	KI-2-1	KI-2-5	KI-2-9
MS	LA21	613.8	580.22	632.52	653.03	640	637.96	605.42
MS-AS	21.22	696.88	604.63	842.98	699.74	767.1	637.46	718.76
	21.23	611.32	614.59	631.42	653	638.58	647.77	602.06
	21.25	610.69	580.72	677.29	653.44	647.6	641.89	601.48
	21.26	942.92	951.44	854.42	926.28	889.24	992.62	926.19
	21.27	750.88	746.12	679.49	793.67	722.74	846.35	703.03

Table (h) Roof displacement of regular and irregular frame under LA22 MS-AS

		KO	KI-0.5-1	KI-0.5-5	KI-0.5-9	KI-2-1	KI-2-5	KI-2-9
MS	LA22	874.6	850.29	908.43	869.3	873.56	845.7	884.69
MS-AS	22.21	874.6	848.93	919.92	870.59	873.78	847.09	897.02
	22.23	875.36	849.96	909.21	871.03	874.33	862.99	884.83
	22.25	917.29	945.57	992.2	871.1	902.8	847.26	994
	22.26	875.55	850.45	909.44	871.1	874.42	846.35	885.1
	22.27	874.6	914.58	913.18	870.59	873.78	847.09	917.38

Table (i) Roof displacement of regular and irregular frame under LA23 MS-AS

		KO	KI-0.5-1	KI-0.5-5	KI-0.5-9	KI-2-1	KI-2-5	KI-2-9
MS	LA23	596.9	574.51	599.29	611.27	606.17	593.21	584.99
MS-AS	23.21	596.12	574.51	599.7	610.75	605.96	593.78	586.32
	23.22	761.9	689.32	793.42	747.99	767.06	720.79	771.46
	23.25	638.8	592.78	633.47	645.66	646.3	629.6	626.48
	23.26	907.88	901.85	918.27	902.01	913.25	909.22	907.8
	23.27	741.41	722.13	749.15	770.64	766.82	740.48	727.89

Table (j) Roof displacement of regular and irregular frame under LA25 MS-AS

		KO	KI-0.5-1	KI-0.5-5	KI-0.5-9	KI-2-1	KI-2-5	KI-2-9
MS	LA25	690.9	674.91	686.69	701.88	698.09	692.85	682.78
MS-AS	25.21	740.91	780.36	731.82	781.18	732.37	747.97	721.04
	25.22	900.58	926.6	929.18	904.41	875.67	885.45	904.05
	25.23	690.89	674.87	686.86	701.9	698.1	692.89	682.73
	25.26	787.7	704.66	798.79	753.79	943.97	761.47	796.86
	25.27	749.24	674.87	767.91	738.1	809.4	714.55	747.23

Table (k) Roof displacement of regular and irregular frame under LA26 MS-AS

		KO	KI-0.5-1	KI-0.5-5	KI-0.5-9	KI-2-1	KI-2-5	KI-2-9
MS	LA26	928.9	898.83	935.92	920.88	939.45	920.66	933
MS-AS	26.21	928.91	899.3	935.91	919.41	939.35	920.43	933
	26.22	928.91	899.3	935.91	919.41	939.35	920.43	933
	26.23	928.91	899.3	935.91	919.41	939.35	920.43	933
	26.25	928.91	899.3	935.91	919.41	939.35	920.43	933
	26.27	928.91	899.3	935.91	919.41	939.35	920.43	933

Table (l) Roof displacement of regular and irregular frame under LA27 MS-AS

		KO	KI-0.5-1	KI-0.5-5	KI-0.5-9	KI-2-1	KI-2-5	KI-2-9
MS	LA27	791	748.82	801.69	812.4	817.47	780.91	780.17
MS-AS	27.21	791.04	748.64	801.63	812.4	817.5	780.88	779.91
	27.22	791.04	748.64	801.63	812.4	817.5	780.88	779.91
	27.23	789.49	747.41	800.05	810.5	815.52	778.87	778.28
	27.25	789.05	746.98	799.5	809.98	814.95	778.39	777.83
	27.26	879.85	941.69	811.44	825.17	998.84	930.91	980.57

Variation of maximum roof displacement for mainshock-aftershock is shown in Figure (a) to Figure (l). :

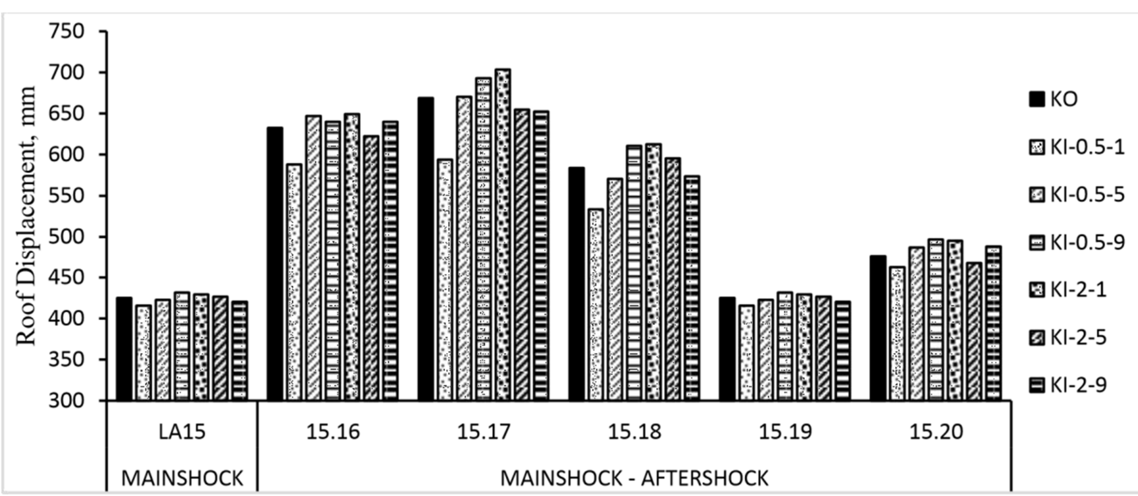

Figure (a) Max. Roof displacement of regular and irregular frame under LA15

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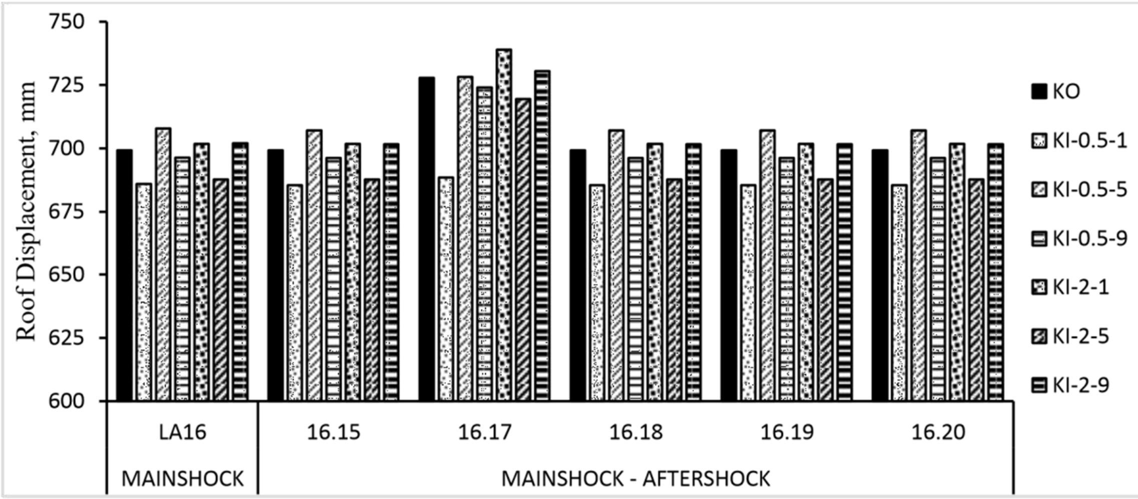

Figure (b) Max. Roof displacement of regular and irregular frame under LA16

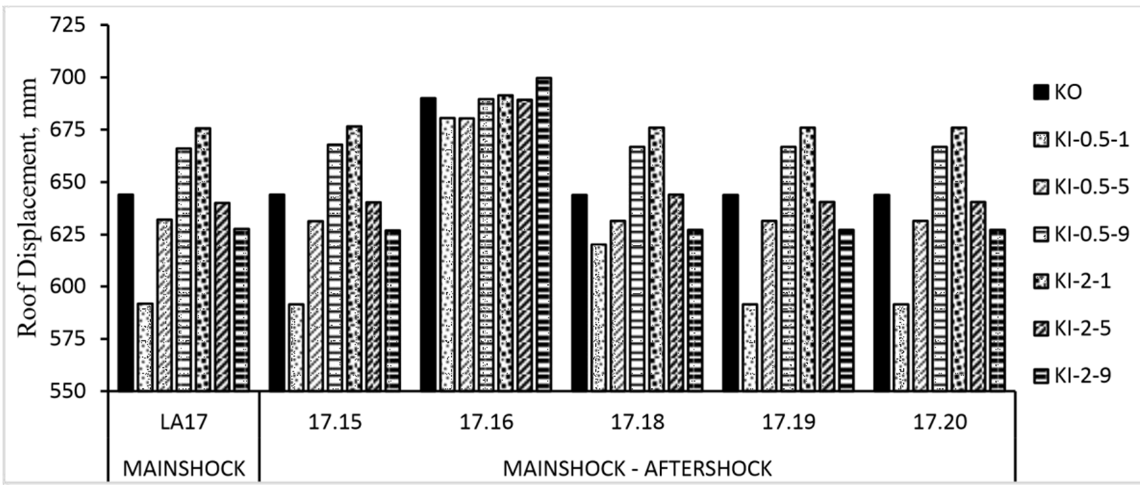

Figure (c) Max. Roof displacement of regular and irregular frame under LA17

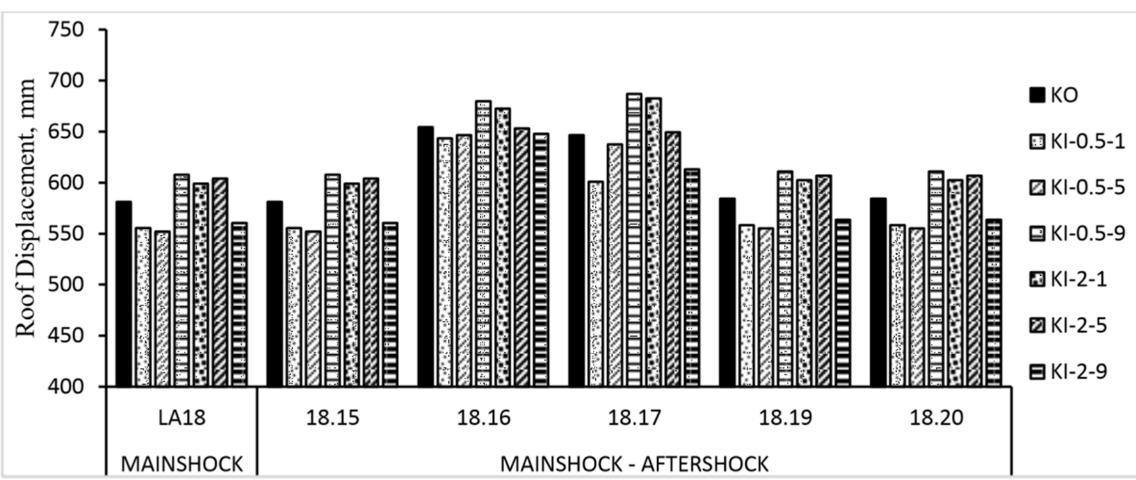

Figure (d) Max. Roof displacement of regular and irregular frame under LA18

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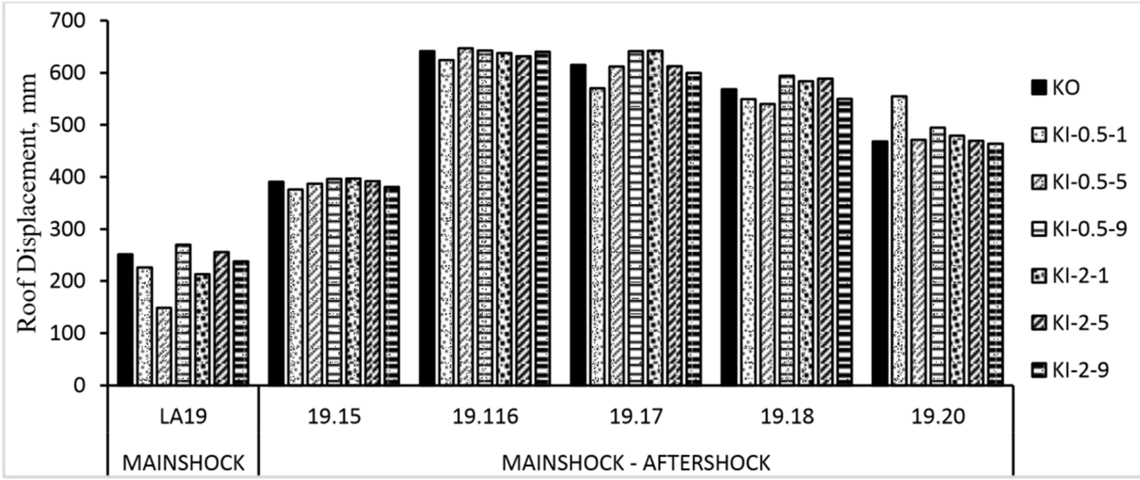

Figure (e) Max. Roof displacement of regular and irregular frame under LA19

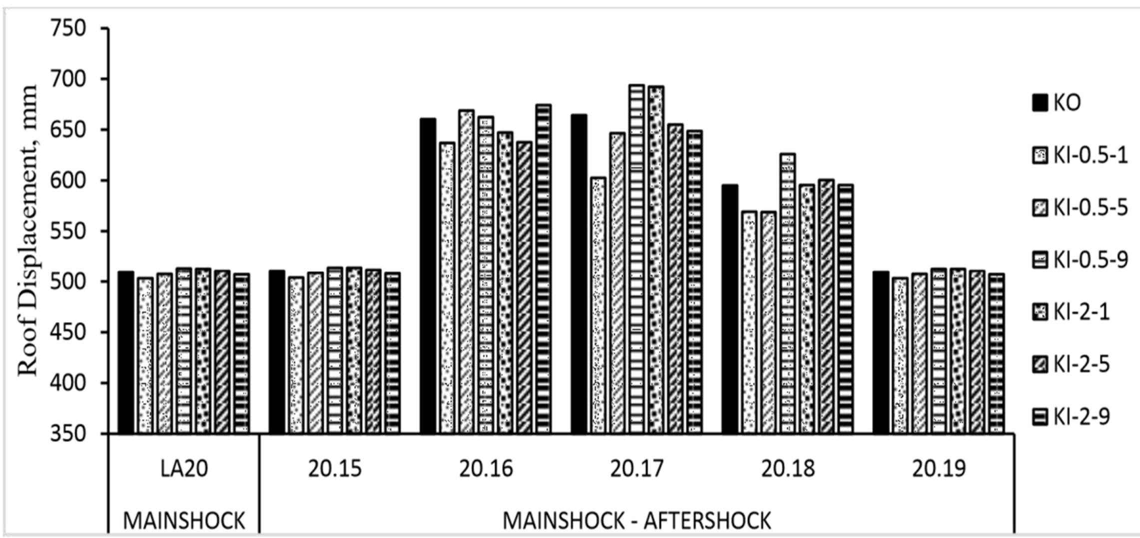

Figure (f) Max. Roof displacement of regular and irregular frame under LA20

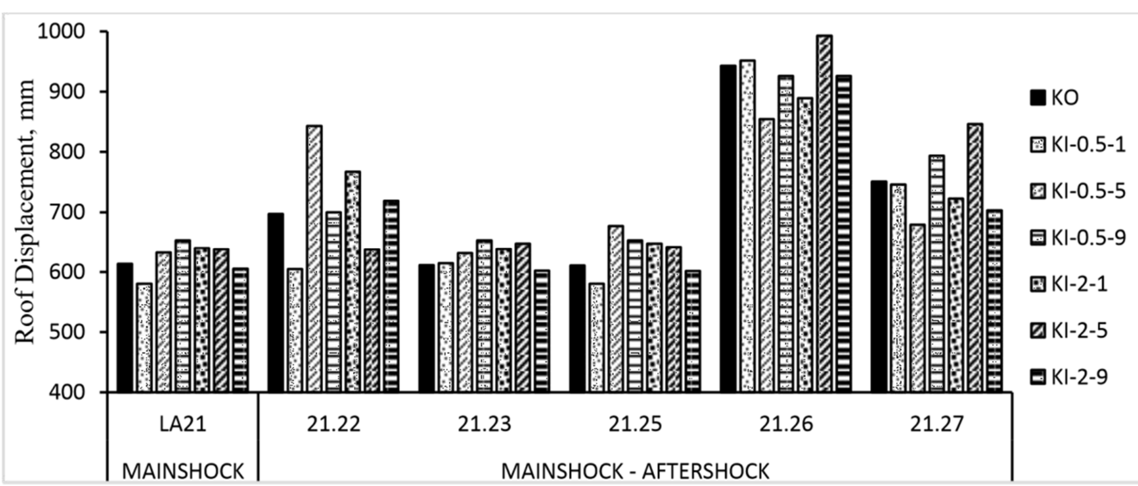

Figure (g) Max. Roof displacement of regular and irregular frame under LA21

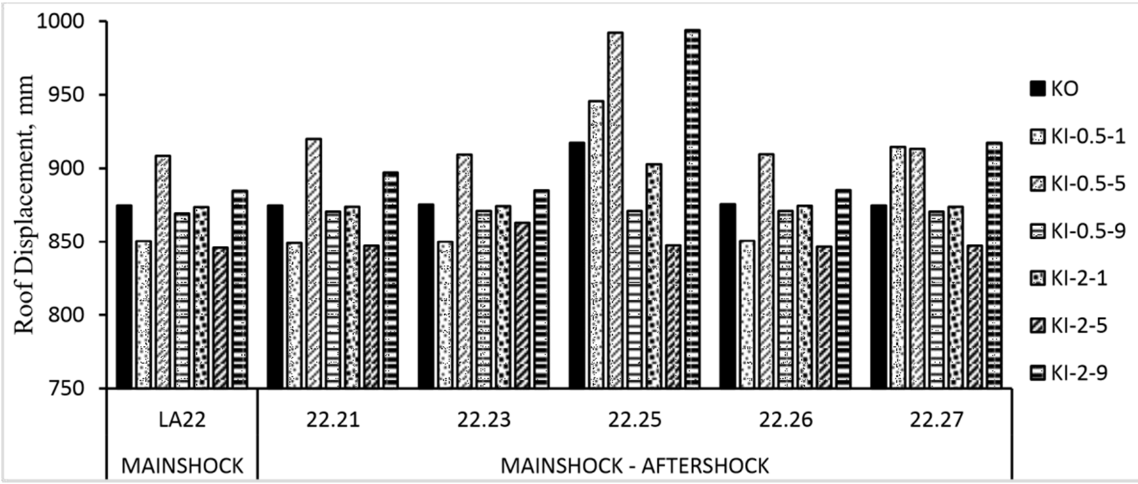

Figure (h) Max. Roof displacement of regular and irregular frame under LA22

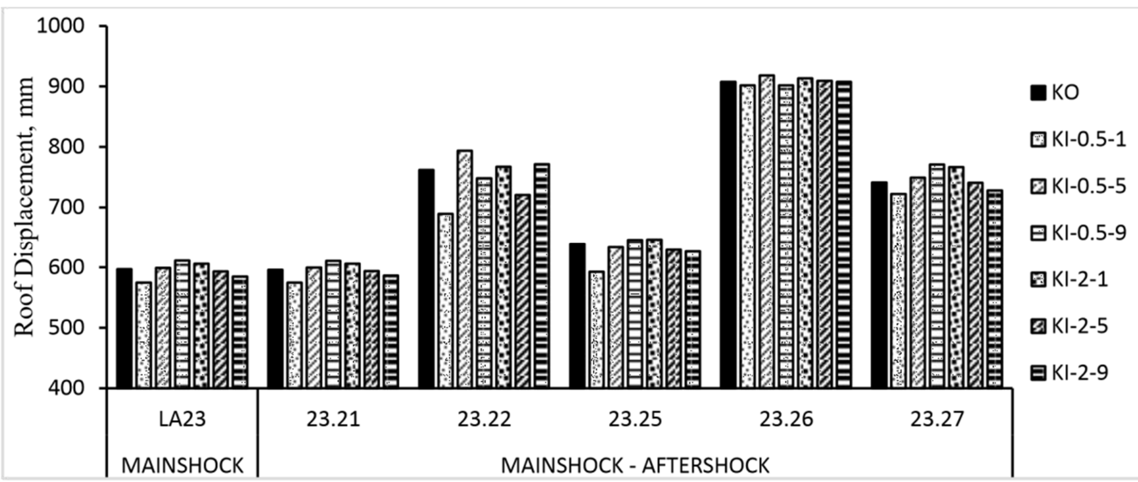

Figure (i) Max. Roof displacement of regular and irregular frame under LA23

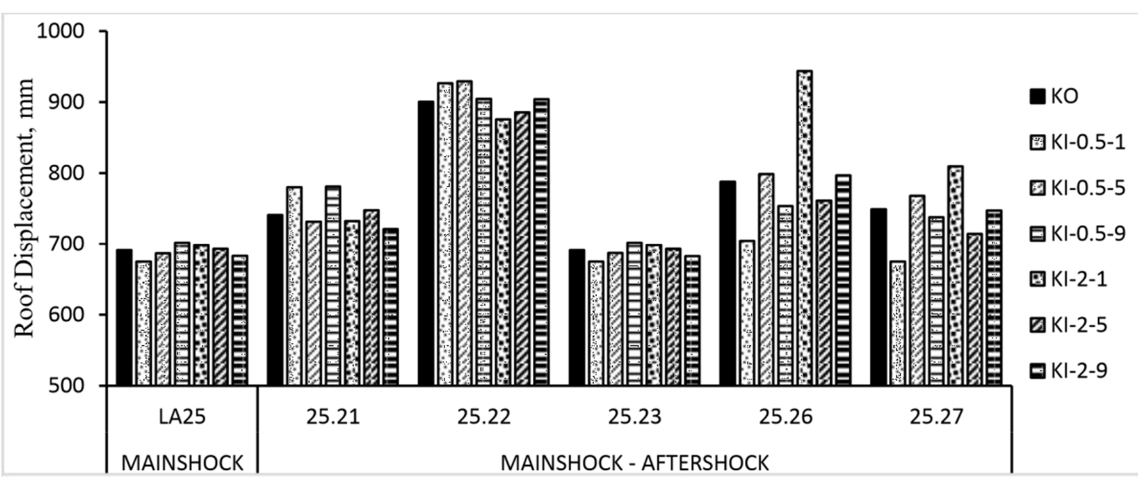

Figure (j) Max. Roof displacement of regular and irregular frame under LA25

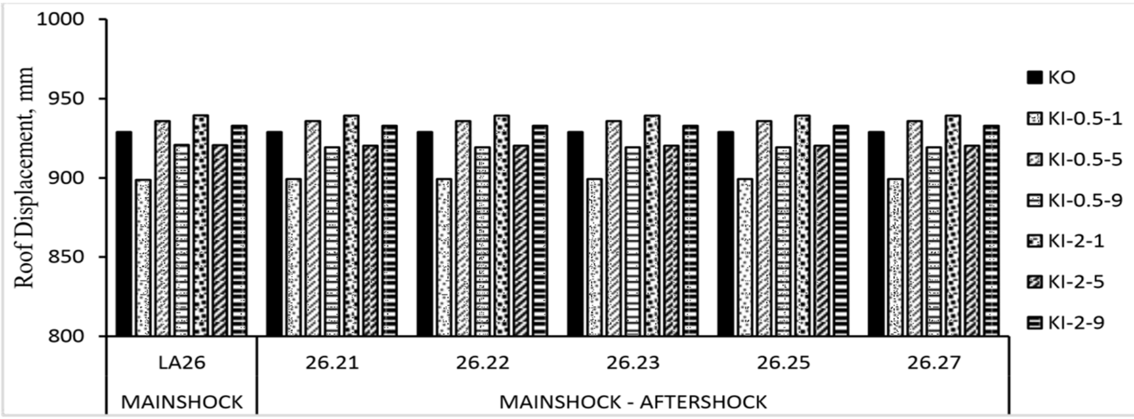

Figure (k) Max. Roof displacement of regular and irregular frame under LA26

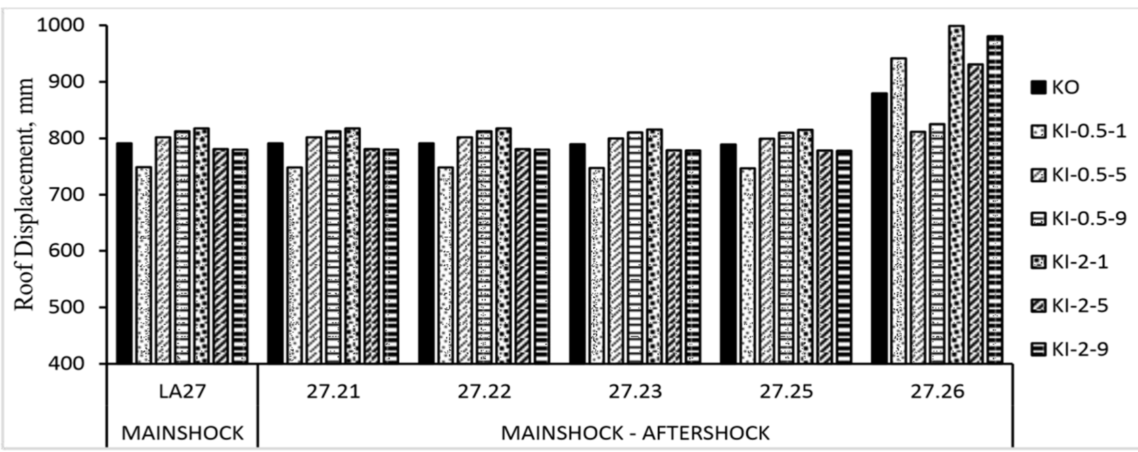

Figure (l) Max. Roof displacement of regular and irregular frame under LA27

Variation of roof displacement of SMRF under mainshock-aftershock 15.16 is shown in Figure 11 and comparison of regular and irregular frames for roof displacement under 15.16 MS-AS is shown in Figure 12. The variation of Storey displacement of regular frame under MS-AS 15.16 is given in Figure 13.

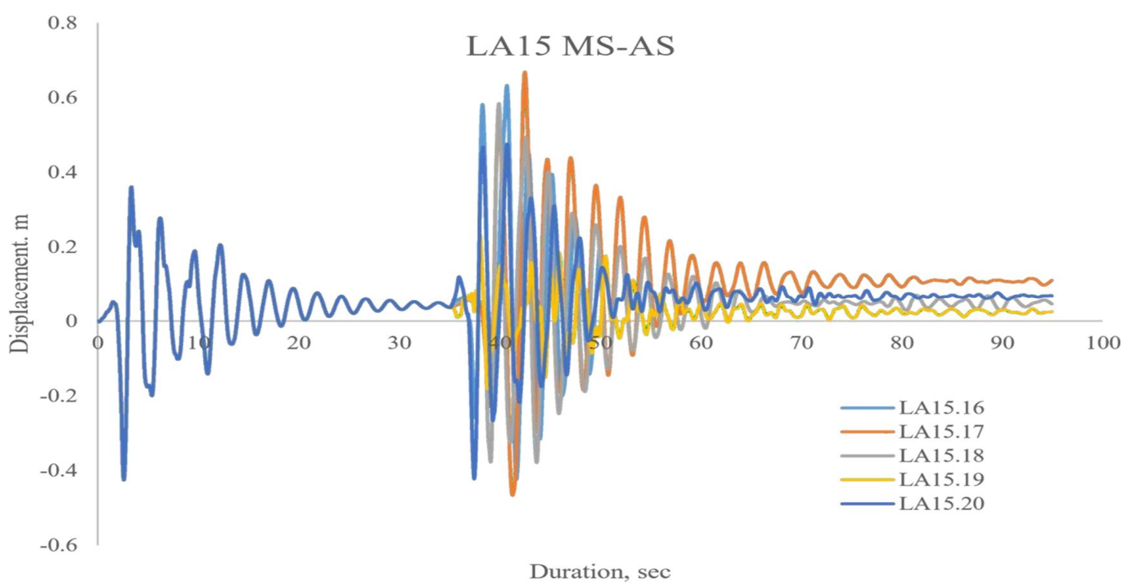

Figure 11 Roof displacement of SMRF under mainshock-aftershock 15.16

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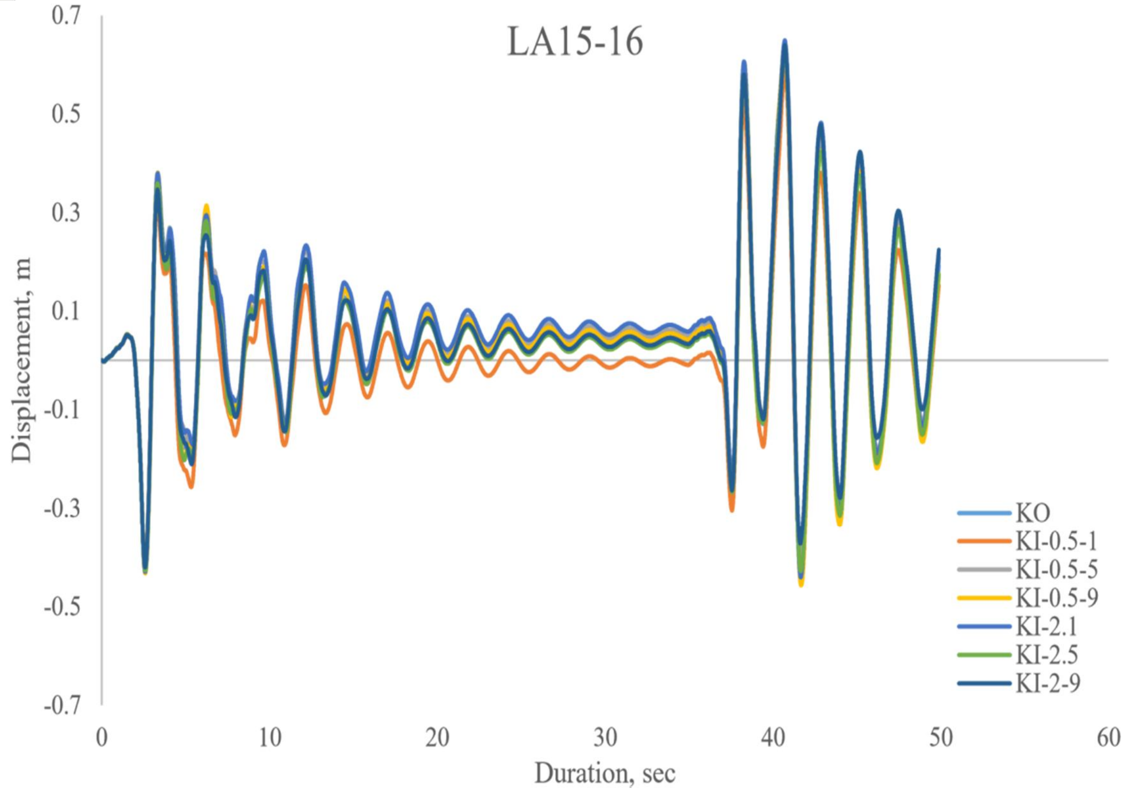

Figure 12 Roof displacement of regular and irregular frames under MS-AS 15.16

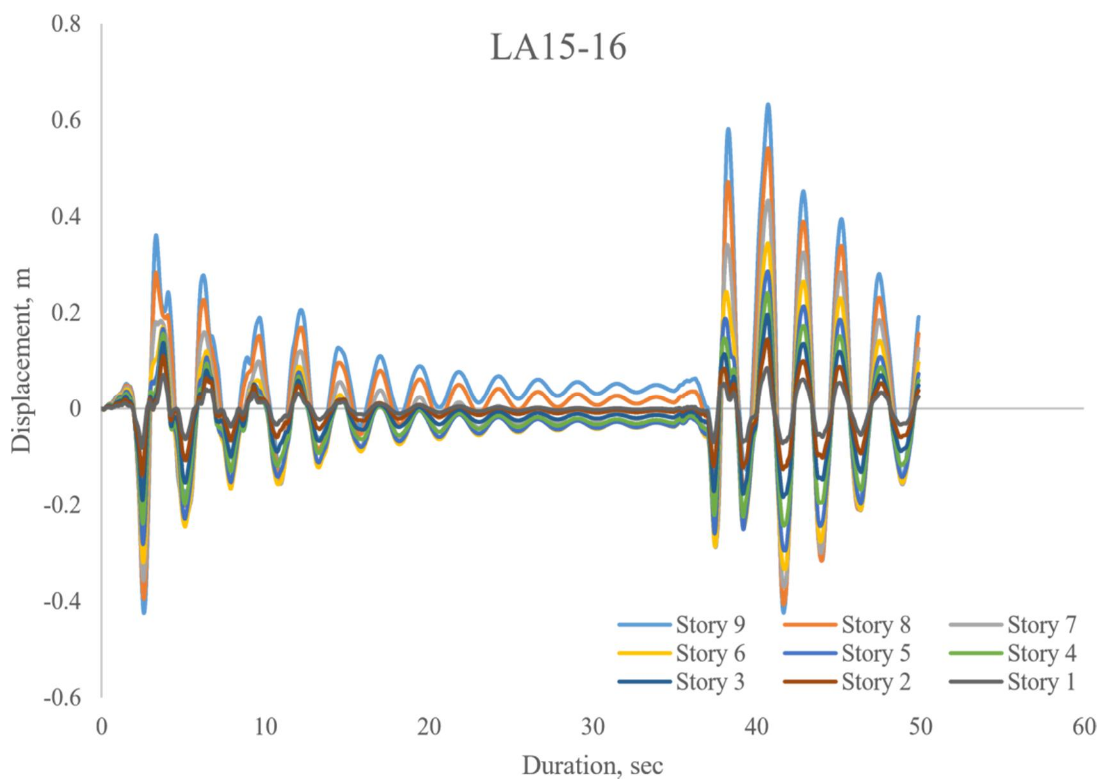

Figure 13 Storey displacement of regular frame under MS-AS 15.16

b) Interstorey Drift Ratio

Interstorey drift ratio of regular and irregular frame structures under mainshock-aftershock ground motion is shown in Figure 14, Figure 15 and Figure 16. Values of interstorey drift ratios are given in Annexure A.

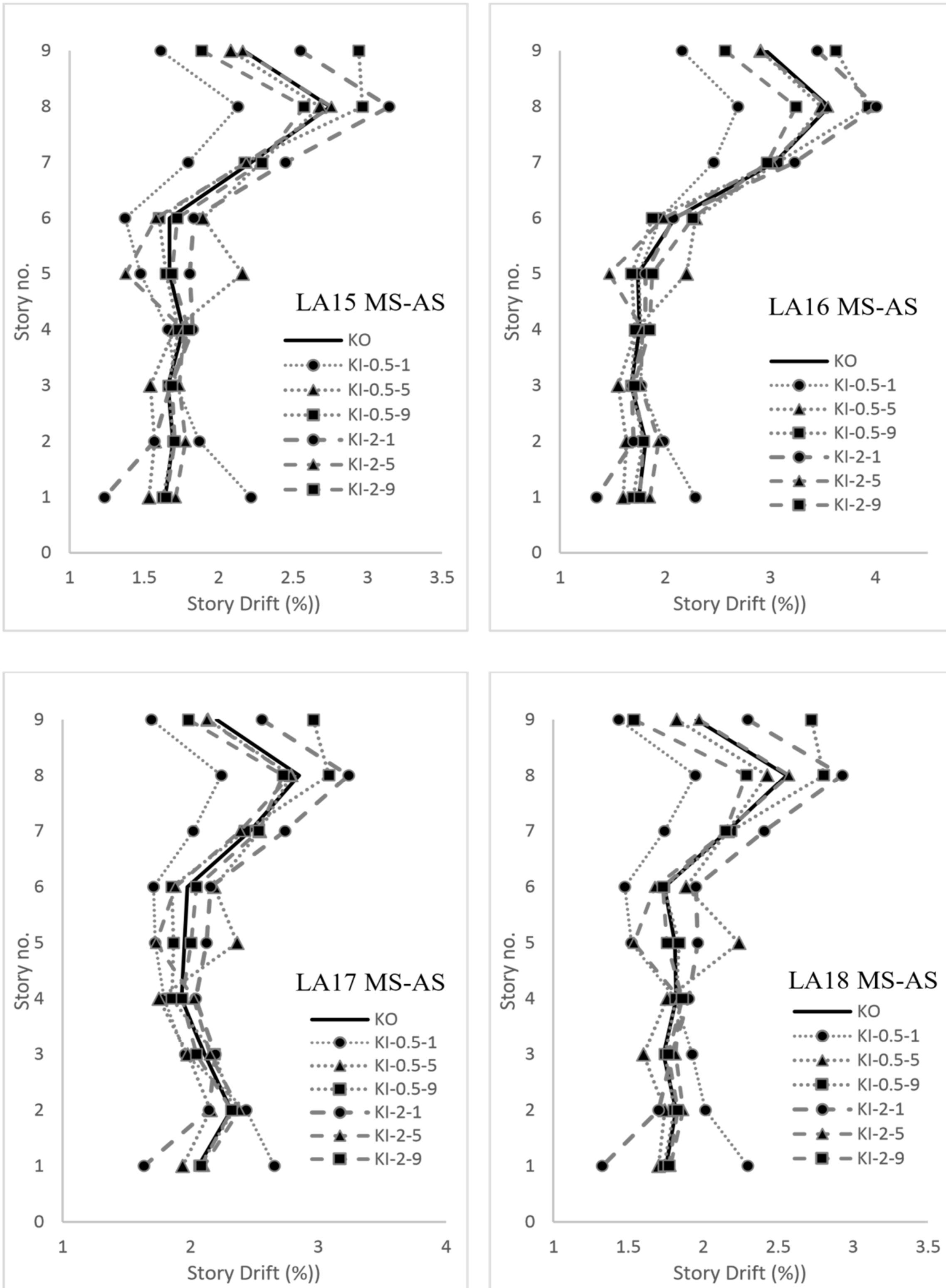

Figure 14 Interstorey drift ratio of regular and irregular frame structures under mainshock LA15, LA16, LA17 andLA18

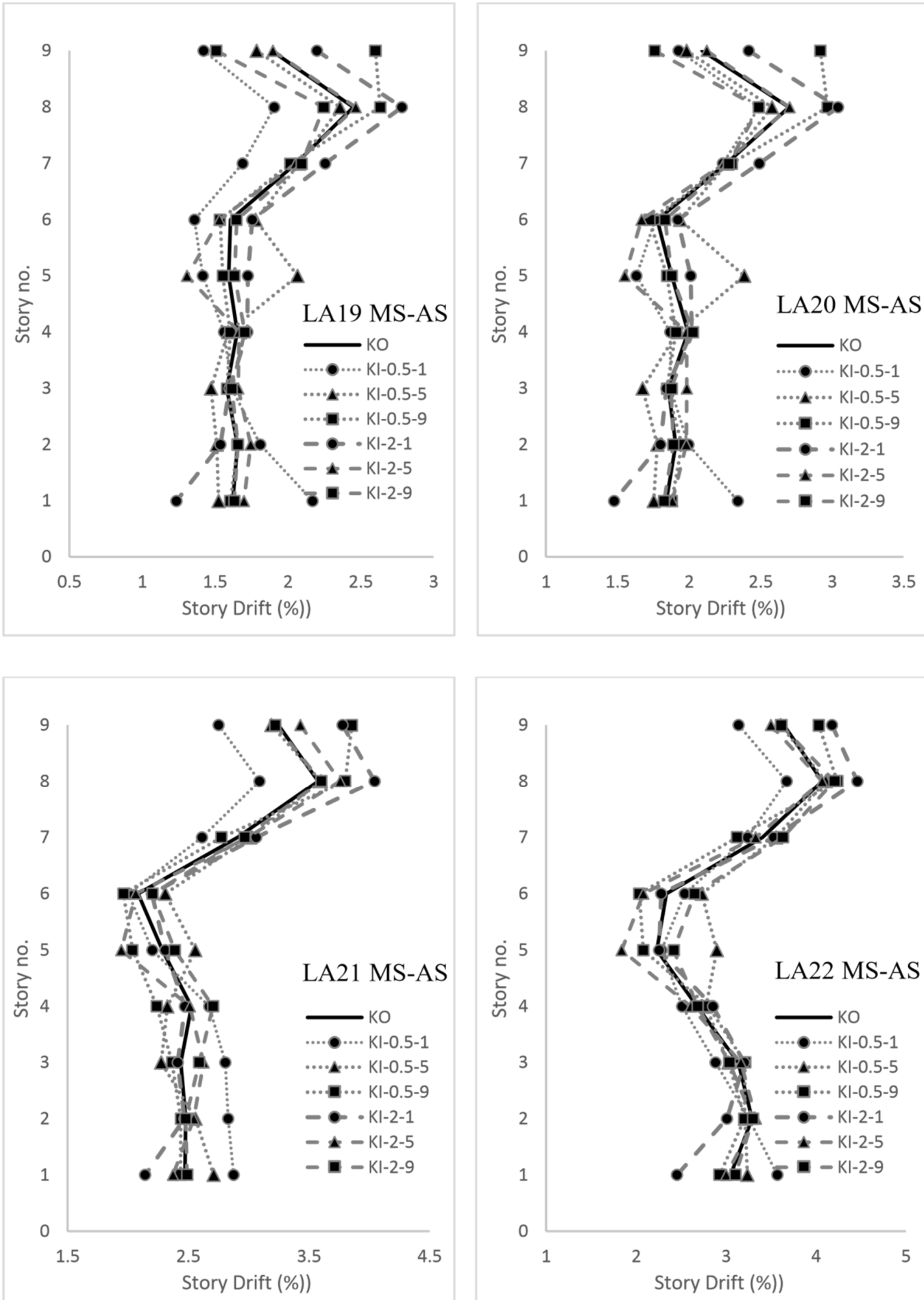

Figure 15 Interstorey drift ratio of regular and irregular frame structures under mainshock LA19, LA20, LA21 andLA22

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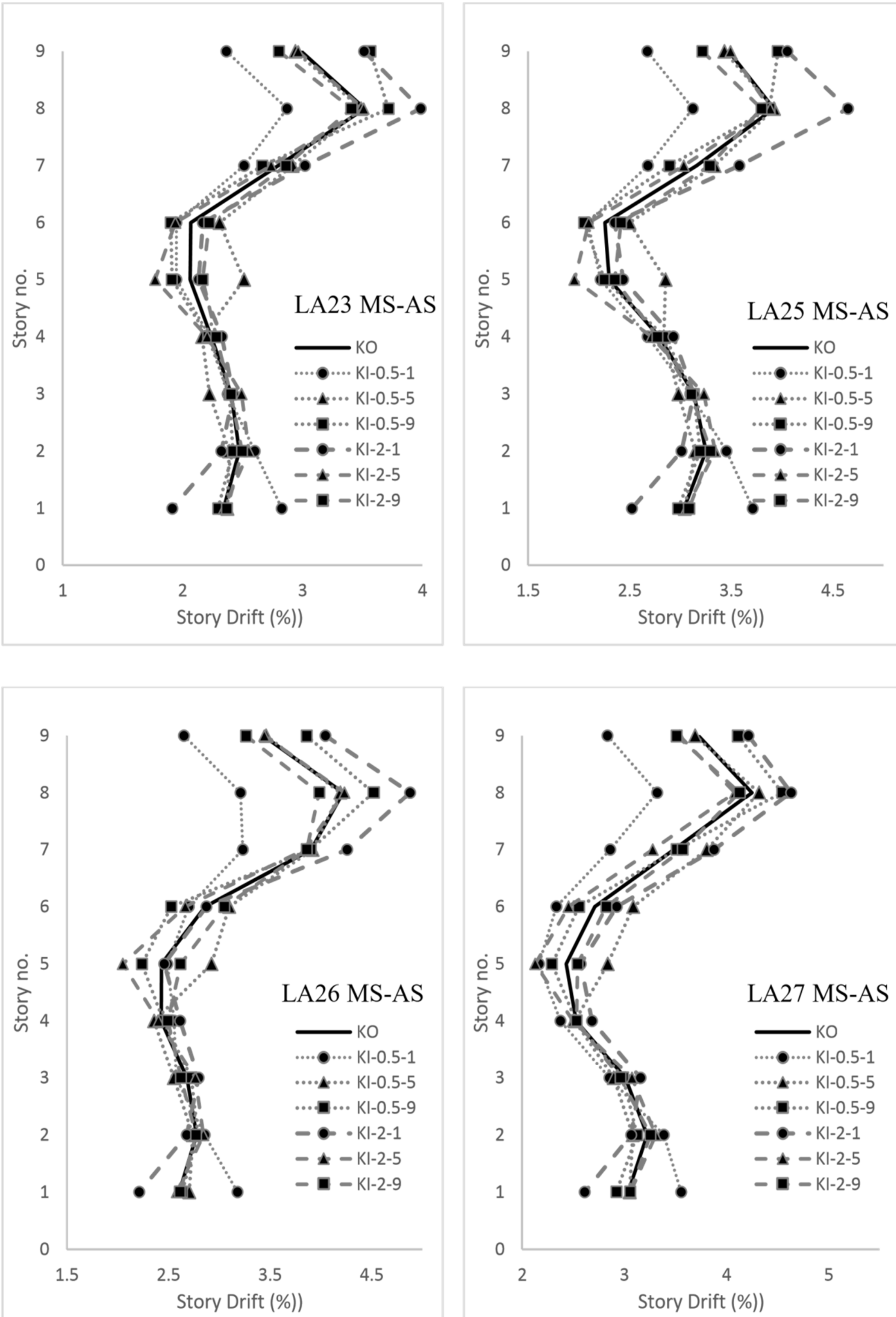

Figure 16 Interstorey drift ratio of regular and irregular frame structures under mainshock LA23, LA25, LA26 andLA27

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3) *Comparison of Mainshock and Mainshock-Aftershock responses*

a) *Responses under 10/50 set of records :*

The drift ratio under MS for regular frame is around 1.5% in bottom stories while in top stories it increases to 2%. 15-25%increment in interstorey drift ratios are observed, when same regular building subjected to MS-AS.

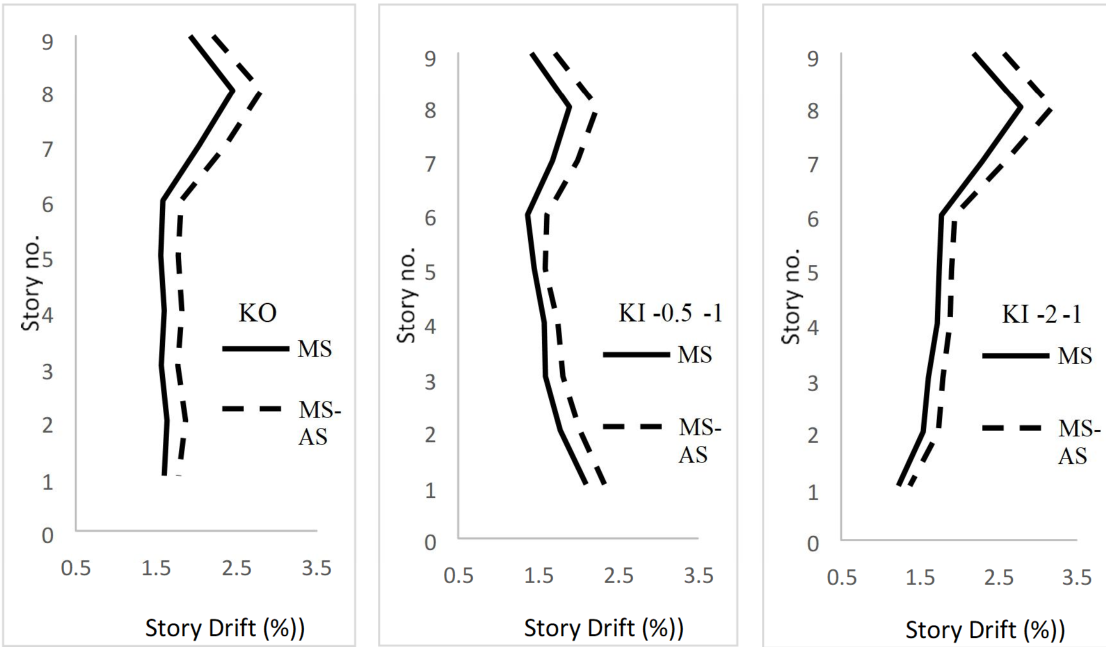

Figure (a) Comparison of MS and MS-AS responses under 10/50 set of record

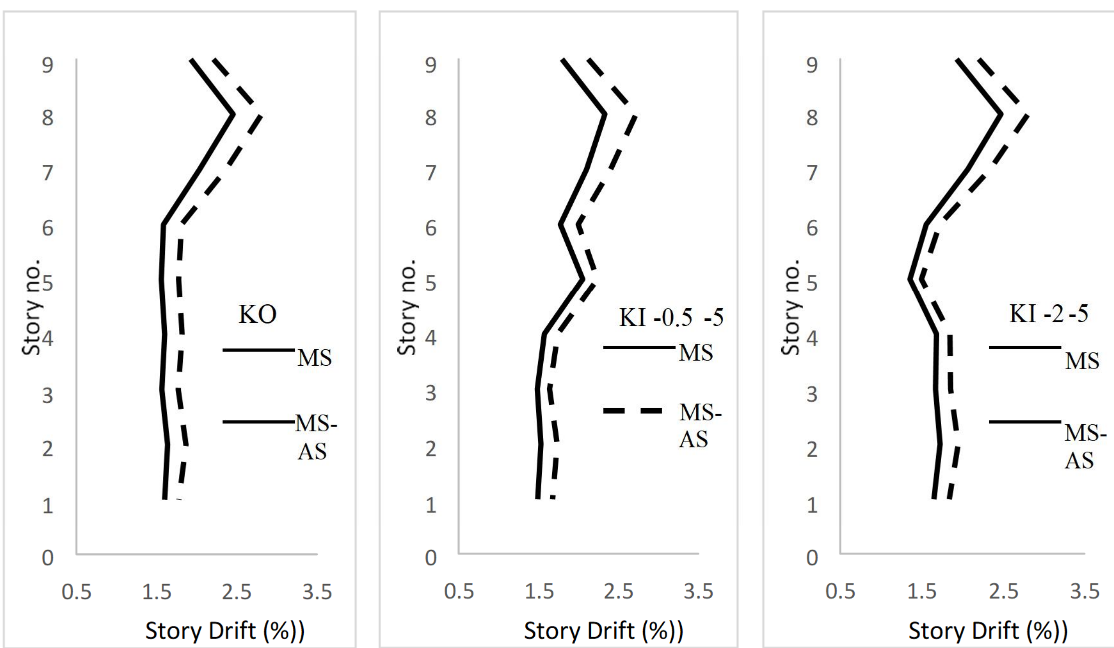

Figure (b) Comparison of MS and MS-AS responses under 10/50 set of record

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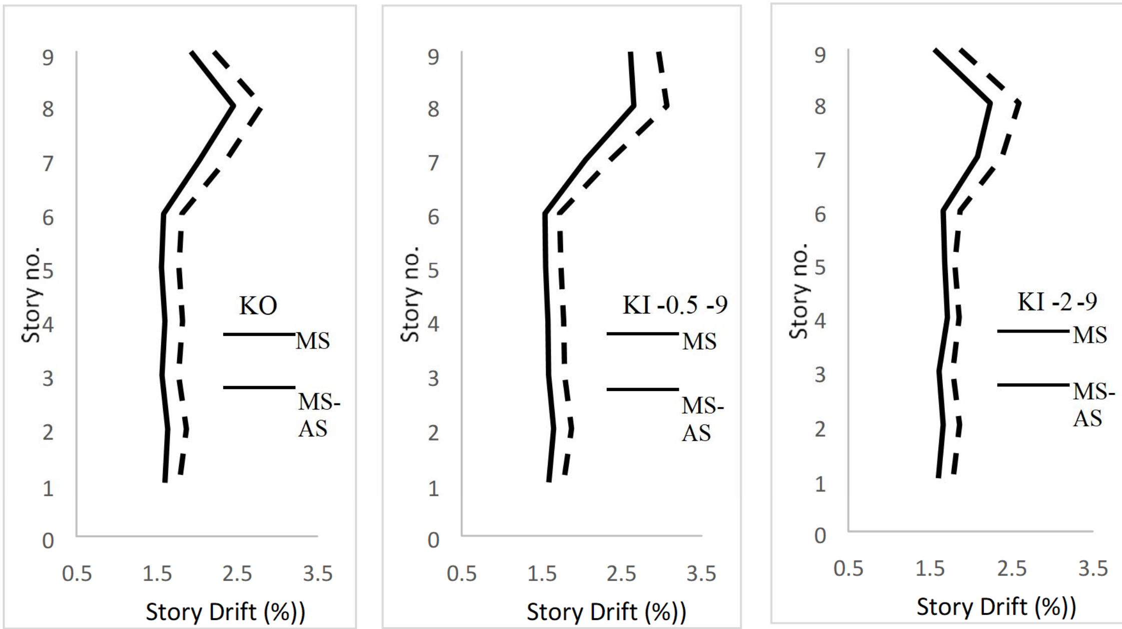

Figure (c) Comparison of MS and MS-AS responses under 10/50 set of record

b) Responses Under 02/50 set of Records

The interstorey drift ratio’s under mainshocks and MS-AS ground motions representing seismic hazard level of 2% probabilityof exceedance in 50 years are shown in Figure 4.10

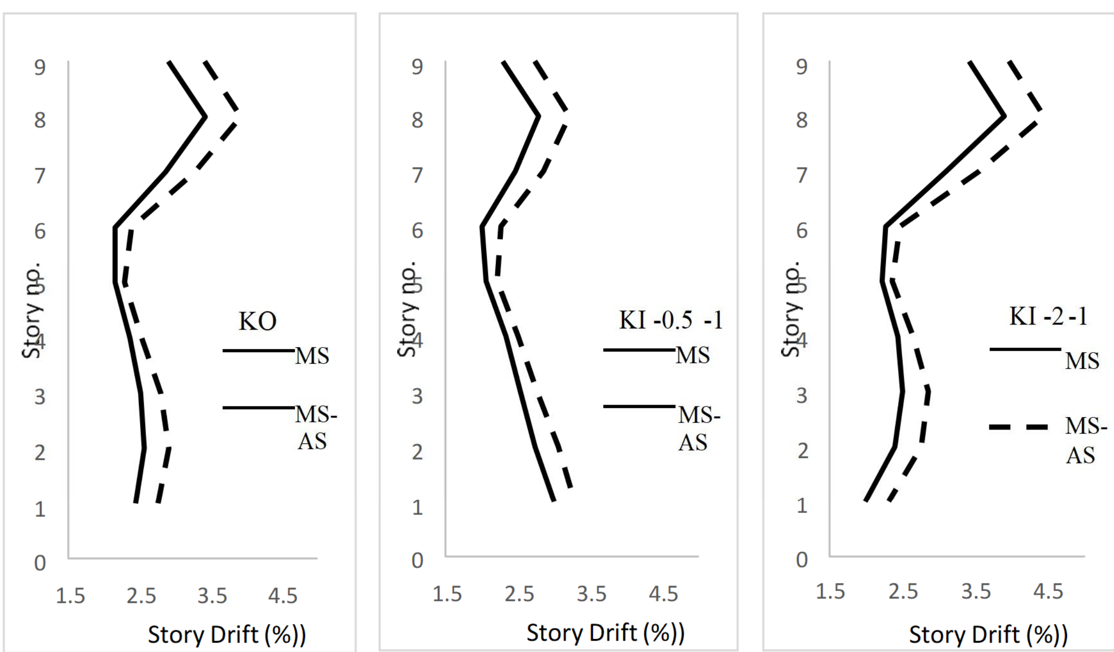

Figure (a) Comparison of MS and MS-AS responses under 2/50 set of record

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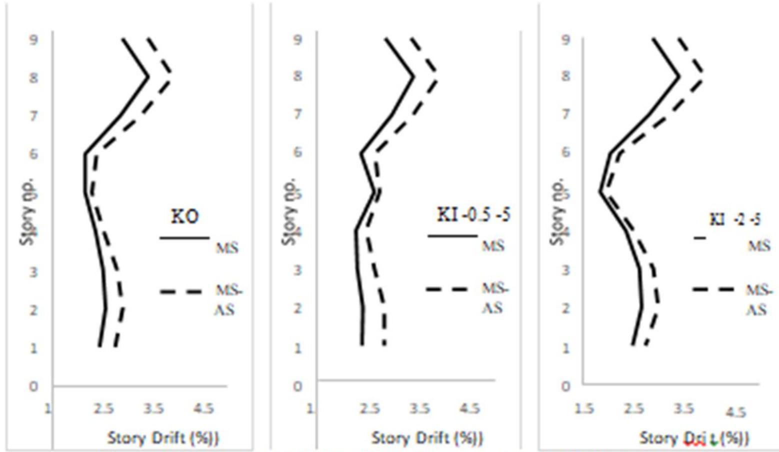

Figure (b) Comparison of MS and MS-AS responses under 2/50 set of record

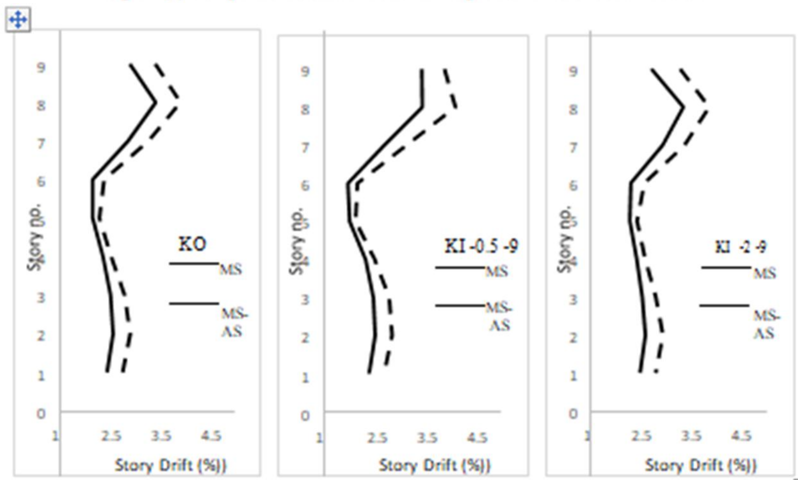

Figure (c) Comparison of MS and MS-AS responses under 2/50 set of record

VII. CONCLUSION

Based on the results from non-linear time history analysis of regular and irregular frame structures under mainshock-aftershock,it is observed the damage from mainshock-aftershock sequences is significantly higher than the damage obtained only from mainshock.

1) Displacement of roof storey goes on decreasing as increasing stiffness in upper stories. Roof displacement is decreased compared to regular building when soft storey irregularity is introduced at bottom storey.
2) Irregularity effect on maximum roof displacement under mainshock-aftershock shown similar responses pattern as shown in mainshock.
3) Stiffness irregularity at bottom storey causes significant effect under both MS and MS-AS.
4) The irregularity at bottom storey shows the maximum inter-storey drift variation when compared to regular frame.
5) The inter-storey drift is more when irregular storey is near base of the building and it is less when irregular storey is near topof the building.
6) Decrease in stiffness of storey causes increase in the inter-storey drift demand in the modified storey and adjacent stories while decreases the inter-storey drift demand in other stories.
7) Increase in stiffness of storey causes decrease in the inter-storey drift demand in the modified storey and adjacent stories while increases the inter-storey drift demand in other stories.
8) Maximum, moderate and minimum variation in inter-storey drift is observed when stiffness irregularity is introduced at bottom storey, mid-storey and top storey respectively.

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