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DAMAGE STATES FOR CONCRETE WALL PIER REINFORCED WITH SHAPE MEMORY ALLOY REBAR

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ABSTRACT: The objective of this study is to determine the effect of parameter for performance damage states of concrete wall pier reinforced with shape memory alloy (SMA). Extensive nonlinear static pushover analyses in the out of plane direction of the rectangular wall pier were performed to determine the following damage states; cracking, yielding and crushing of SMA-RC wall pier. Uncertainties in different structural and geometric parameters of the wall pier are taken into consideration through multifactorial analysis of variance (ANOVA). From detailed parametric analyses, it was concluded that the height to thickness ratio (H/t) and skew angles are the most significant factors influencing the performance damage state of SMA-RC wall piers. Other significant factors including concrete compression strength, austenite to martensite starting stress, vertical and transverse reinforcement ratio, and aspect ratio are also discussed along with their effect on different performance damage states of SMA-RC wall piers.

1. Introduction

Bridges are an essential part of a country's civil infrastructure that plays a vital role in the transportation network. However, the continuity of transportation system is under threat since many of these bridges are vulnerable to seismic events because of design deficiencies (Andrawes et al., 2009; Wu et al., 2008). The design problem often associated with material and geometric factors. This problem can result in various occurrences such as shear failure, flexural ductility failure, plastic hinge failure and confinement failure. To understand the behavior of the bridge, it is necessary to identify the main factors that affect the performance damage levels. The uncertainties of geometric and material parameters that influence the behaviour of reinforced concrete bridge pier have been investigated by some researchers (Yang et al., 2015; Reza et al., 2014; Padgett and Desroches, 2007). For example, Reza et al. (2014) proposed several equations that can predict different damage levels, which were derived, based on the effect of material and geometric factors.

Towards the performance-based seismic design approach, it is necessary to enhance the ductility and deformation of the bridge structure to maintain the integrity and functionality of the bridge system. Researchers have suggested innovative systems using smart materials such as shape memory alloy (SMA) for enhancing the performance of bridge under seismic response (Billah and Alam 2014, Saiidi et al., 2009). Application of SMA in a structural system has demonstrated a great potential in improving the performance of civil structures located in seismic regions (Alam et al. 2007). This promising behavior of SMA has encouraged researchers all over the world to develop new methods for using SMA as reinforcement bars (Alam et al., 2008; Saiidi and Wang, 2006) and retrofit method (Andrawes et al., 2009) in concrete structures. Although the existing literature for SMA is well documented, there is still limited study on the application of SMA as reinforcement bars in wall bridge pier. The present study explores the effect of different material and geometric parameters on the damage states of RC wall pier reinforced with different types of SMA. This study specifies the significant parameters of geometric and material properties that effect on the drift of damage levels using a fractional factorial design of the experiment.

2. Description of wall bridge pier

2.1. Geometry and material parameters of wall bridge pier

The structural and geometrical parameters considered in this research include concrete compressive strength (f'_c), steel yield strength (f_y), confinement reinforcement ratio, longitudinal reinforcement ratio (ρ_v), transverse reinforcement ratio (ρ_h), aspect ratio (H/L), height to thickness ratio (H/t) and skew angle ($\varnothing$). In order to investigate the performance damage states of RC wall pier using SMA, three different types of austenite to martensite starting stress of SMA are used throughout this study. The selected ranges of parametric values considered in this study are listed in Table 1. To perform this parametric study, a total of 81 wall pier models (3^{8-4} = 81 models) are created where parameters are determined using fractional factorial design (revolution IV) (Montogomery, 2009). Nonlinear static pushover analyses are performed using Seismostruct finite element software to capture different drift limits corresponding to cracking of concrete cover, yielding of SMA in plastic hinge region, spalling of concrete cover, and crushing of core concrete (Seismosoft, 2013).

Table 1 – **Parameters considered for the performance damage states**

Parameter	Units	Value		
Concrete Compressive Strength, f'_c	(Mpa)	30	45	60
Steel Yield Strength, f_y	(Mpa)	300	400	500
Confinement Reinforcement ratio		Low	Medium	High
Vertical Reinforcement ratio, ρ_v	(%)	0.25	0.875	1.5
Transverse Reinforcement Ratio, ρ_h	(%)	0.08	0.19	0.3
Aspect Ratio, H/L		0.35	0.675	1
Wall height to thickness Ratio, H/t		4	8	12
Skew Angle, $\varnothing$	(Degree)	0	15	30
Austenite to Martensite starting stress of SMA, $f_{y\text{-}sma}$	(Mpa)	320	410	435

In this study, SMA is used as vertical reinforcement and placed only at the bottom plastic hinge region of the wall piers. In other locations, steel reinforcement are used. The plastic hinge length of SMA reinforced wall piers is calculated using Eq. 1 (Paulay and Priestley, 1992).

$$L_p = 0.08L + 0.022 d_b f_y \tag{1}$$

Here, L is the length of the member in mm, which represented the height of wall, d_b is the diameter of rebar in mm and f_y is the yield strength of the reinforcement in Mpa, respectively. The SMA properties used in this study are collected from other studies (Alam et al., 2008; Omori et al., 2011; Ghassemieh et al., 2012) as shown in Table 2.

Table 2 – **Properties of different types of shape memory alloy (SMA)**

Alloy	E (Gpa)	f_y (Mpa)	f_{p1} (Mpa)	f_{t1} (Mpa)	f_{t2} (Mpa)	ε_s (%)	Reference
$NiTi_{45}$	62.5	401	510	370	130	6	Alam et al. (2008)
$NiTi_{45}$	68	435	535	335	170	8	Ghassemiah et al. (2012)
FeMnAlNi	98.4	320	442.5	210.8	122	6.13	Omari et al. (2011)

E = modulus of elasticity; f_y= austenite to martensite starting stress; f_{p1}= austenite to martensite finishing stress; f_{t1}= martensite to austenite starting stress; f_{t2}= martensite to austenite finishing stress; and ε_s = superelastic plateau strain

Multifactorial analysis of variance (ANOVA) is used to perform the parametric study of SMA-RC wall piers with different combinations of factors. ANOVA is a statistical tool that provides a way to measure differences between two or more factors by analyzing the variance. A p-value of 5% is considered for a testing statistical significance level of these factors. Therefore, the parameters having a p-value less than 0.05 are considered as significant factors (Montogomery, 2009). The performance damage states in terms of drift at concrete cracking, concrete spalling, SMA yielding, and core concrete crushing are monitored as responses in ANOVA. Here, drift ratio at various damage levels is defined as the damage displacement to the height of the wall pier. Three levels (low, medium, and high) for each factor are considered in the ANOVA to analyze the effect of different factors on the performance damage state of the SMA RC wall pier.

2.2. Pushover analysis

In this research, the drift limit states of SMA RC wall piers are identified corresponding to strain values. The performance levels under consideration are cover concrete cracking, SMA yielding, and core concrete crushing. The cracking strain has been assumed as $0.60\sqrt{f'c}/E_c$. Meanwhile the 0.004 strain for concrete spalling as suggested by Priestley et al. (1996). The yield strain of SMA is defined as the austenite to martensite starting stress (f_y) divided by the elastic modulus (E) at austenite phase. The crushing strain is defined using Eq. 2

$$\varepsilon_{cu} = 0.004 + 1.4\rho_s f_{yh}\varepsilon_{sm} / f'_{cc} \tag{2}$$

Where,, ε_{cu} is the ultimate compression strain, ε_{sm} is the steel strain at maximum tensile stress, f'_{cc} is the concrete compressive strength in MPa, f_{yh} is the yield strength of transverse steel in MPa, and ρ_s is the volumetric ratio of confining steel. The drift ratio then defined as the dispalcement at the onset of a particular damage levels to the height of the wall. To investigate the performance of damage states for SMA-RC wall pier, the nonlinear pushover analysis is performed using three-dimensional finite element model developed in Seismostruct. The SMA-RC wall pier is tested using incremental displacement by applying a lateral load in the weak direction as shown in Figure 1 (out of the plane). Each model is subjected to an axial load that represents 5% load index based on concrete properties.

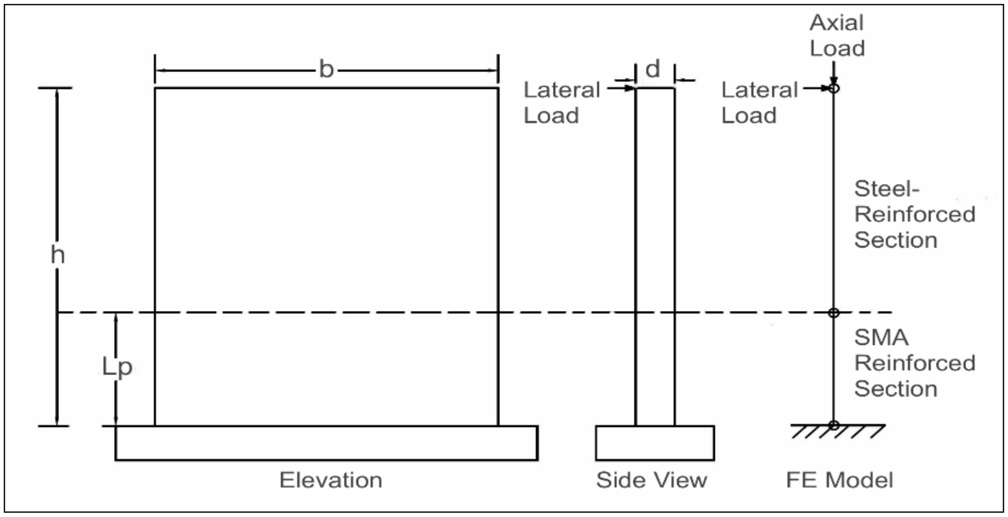

Fig. 1 – Model of SMA-RC wall pier

3. Results and discussion

3.1. Parametric study

From ANOVA, the most significant parameters that affect the performance damage states of SMA RC wall piers are determined. The results are summarized in Table 2. This table reports the *p*-values of each factor for cracking, spalling, SMA yielding and crushing. Based on *P* values (≤ 0.05), it is found that height to thickness ratio (*H/t*) of the wall piers and skew angle are statistically the most significant factors for all performance damage states (cracking, spalling, SMA yielding and crushing). Other significant factors that influence cracking drift limits are concrete compressive strength and aspect ratio of the walls as highlighted in Table 2. Spalling and SMA yielding have similar influential factors including the austenite to martensite starting stress of SMA and vertical reinforcement ratio. On the other hand, longitudinal and transverse reinforcement ratios are found to have the most significant effect on the concrete crushing drift limit.

Figure 2 shows the drift distribution for different performance limit states of SMA-RC wall pier using box plots. The horizontal lines in the middle of the boxes represent median drift values for different damage states (cracking, spalling, yielding and crushing). From Figure 2, the median drift values of first cracking, first spalling, first SMA yielding and first crushing are 0.12%, 0.85 %, 1.25% and 2.26%, respectively. Here, the spalling of cover concrete occurred before the yielding of the SMA rebar. The effectiveness of SMA rebar in resisting more forces after cracking has caused the yielding of SMA occurs after spalling.Thus, SMA-RC wall bridge pier experiences to sustain higher deformation after concrete cracking occurred (Billah and Alam 2014). This observation has similar trend reported by Billah and Alam (2014); Saiidi and Wang (2006).

Table 2 – P values corresponding to drift of damage from multifactor ANOVA

	Main Factors	**Cracking**	**Spalling**	**SMA Yielding**	**Crushing**
A	Concrete Compressive Strength, f'_c	***0.000***	0.287	0.283	0.239
B	Austenite to Martensite starting stress, $f_{y\text{-}SMA}$	0.317	***0.008***	***0.000***	0.827
C	Vertical Reinforcement ratio, ρ_v (%)	0.534	***0.000***	***0.003***	***0.002***
D	Transverse Reinforcement Ratio, ρ_h (%)	0.142	0.995	0.75	***0.013***
E	Confinement Reinforcement Ratio	0.773	0.664	0.497	0.381
F	Aspect Ratio (*H/L*)	***0.043***	0.682	0.157	0.418
G	H/t Ratio	***0.000***	***0.000***	***0.000***	***0.000***
H	Skew Angle, Θ	***0.004***	***0.003***	***0.000***	***0.049***

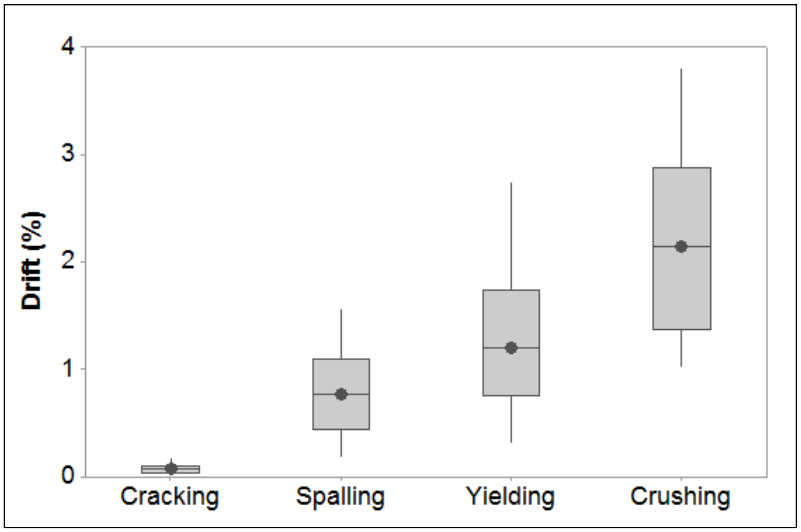

Fig. 3 – Box plot for different performance damage states

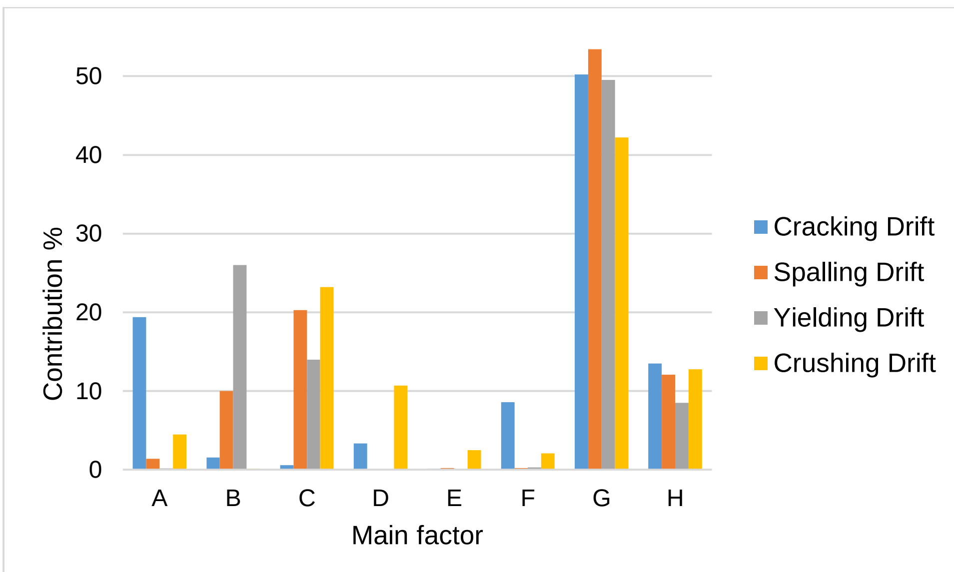

Fig. 3 – Percentage of contribution of main factors

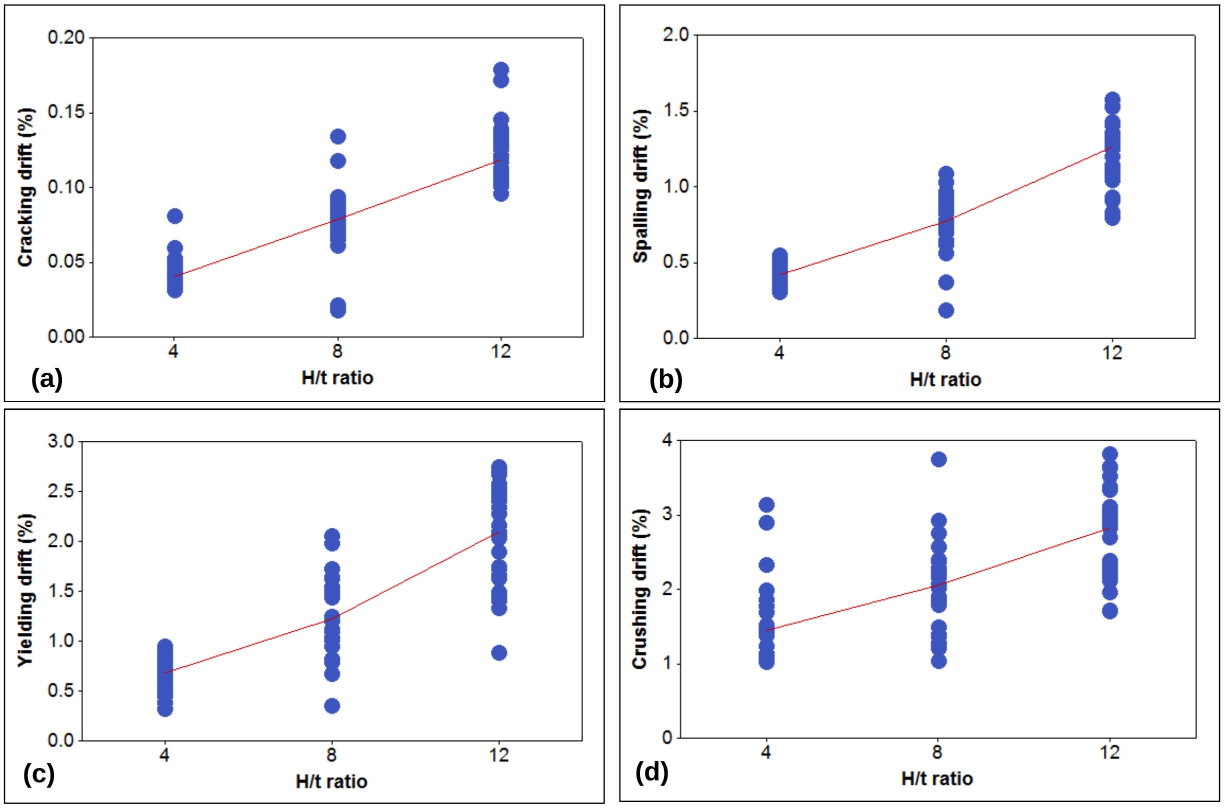

Fig. 4 – Range and variation of median drift for H/t ratio at different performance damage levels (a) cracking (b) spalling (c) yielding and (d) crushing.

3.2. Effect of significant factors

The contribution of main factor that influence the performance drift of SMA-RC wall bridge pier illustrated in Figure 3. From the observation, percentage contribution of H/t ratio is higher than other factors. The percentage contribution obtained for H/t ratio on cracking drift, spalling drift, yielding drift and crushing drift are 50.2%, 53.4%, 49.5% and 42.2%, respectively. Meanwhile, the skew angle has 13.5%, 12.1%, 8.5% and 12.8% from total response variability. Other important factors that effect on cracking drift are concrete compression strength and aspect ratio with percent contribution 19.4% and 8.6%. The total percentage contribution of other significant factor that affect spalling and yielding drift are 30.3% and 40%, respectively. The vertical and transverse reinforcement ratio contribute about 23.2% and 10.7% on crushing drift.

The distribution ranges of the most significant factors (H/t ratio and skew angle) for different performance damage states are illustrated in Figures 4 and 5. The drift was calculated based on median values of performance damage states versus the most influenced parameters. From Figure 4 (a)-(d), it can be seen that the effect of increasing height to thickness ratio (H/t) becomes more significant on cracking, spalling, SMA yielding and crushing drifts. As expected and shown in Figure 5 (a)-(d), the drift at different damage levels decreases when the skew angle increases. It is because when the skew angles are introduced at SMA-RC wall bridge pier, the skewed wall bridge piers tend to rotate and becomes more prone to damage due to additional stress component. A wide range of drift damage states was observed for both trend. This trend is probably resulting from other combination main factors.

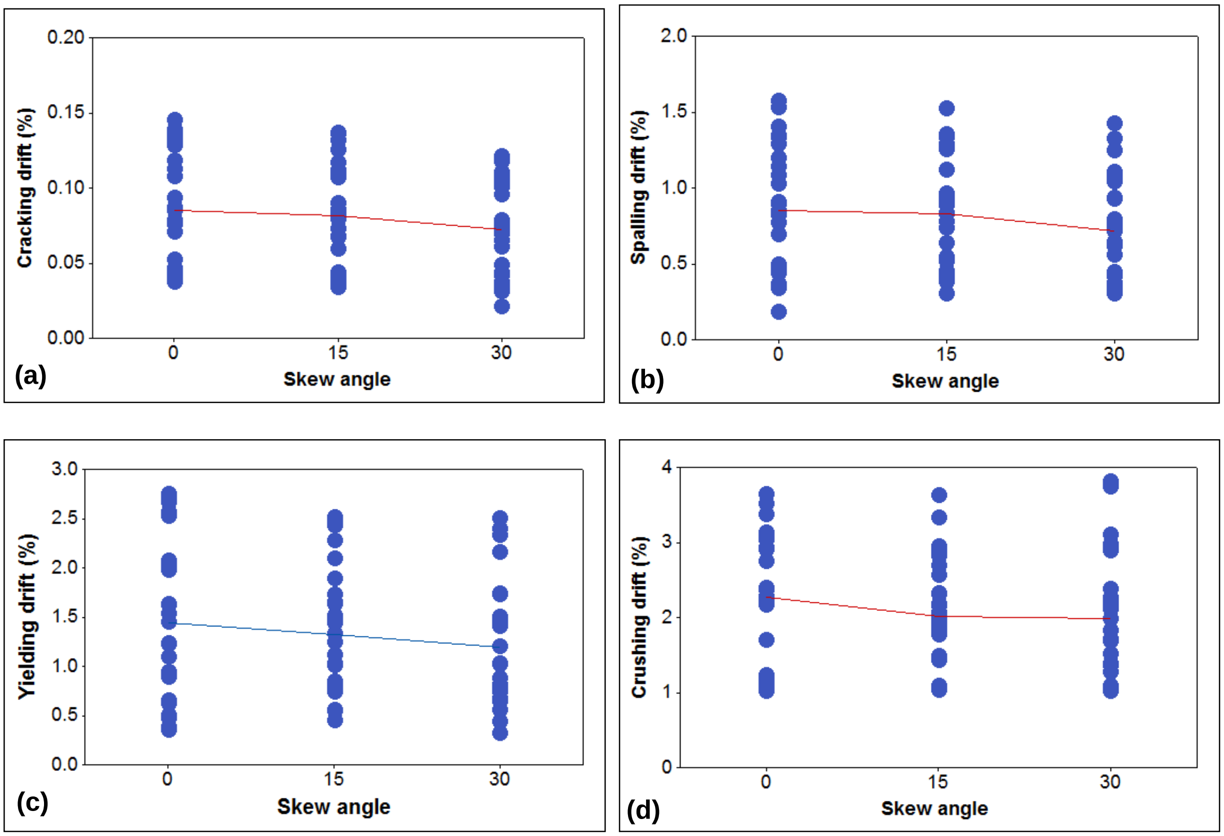

Fig. 5 – Range and variation of median drift for the skew angle at different performance damage levels (a) cracking (b) spalling (c) yielding and (d) crushing.

The contribution of vertical reinforcement is significantly effect on yielding and crushing drift with 40% and 23.2% from total response as shown in Figure 3. Here, SMA is used as vertical reinforcement bars and placed at the critical region. Similar finding was reported by Abo-Shadi et al. (2000). The authors concluded that the vertical reinforcement ratio is associated with high yield curvatures that significantly influence the yield deflection. As a results, SMA experiences a higher deformation before yielding and sustains large deformation before crushing, thus increasing the drift limits.

4. Conclusion

Finite element simulation has been employed to investigate the effect of various parameters on the performance damage states of concrete wall bridge pier reinforced with SMA. A total of 81 pushover analyses of SMA-RC wall pier models with varying parameters has been conducted. The significant parameter was quantified using analysis of variance (ANOVA). Based on the observations, following conclusions can be made:

1. The height to wall thickness ratio (H/t) and skew angle have the most significant effects on drift limit for concrete cracking, concrete spalling, SMA yielding, and concrete crushing with 50.2%, 53.4%, 49.5% and 42.2%, percentage contribution compared to other geometrical and material parameters.

2. The other important factors that affect the drift at different damage state were concrete compression strength, aspect ratio H/L, the austenite to martensite starting stress of SMA, longitudinal and transverse reinforcement ratio.
3. Spalling occurred before the yielding of SMA. Therefore, the progressions of the performance damage states for concrete wall pier reinforced with SMA are cracking, spalling, yielding, and crushing.
4. The median drift at different damage levels is 0.12, 0.85, 1.25 and 2.26 corresponding to cracking, cover concrete spalling, SMA yielding, and core concrete crushing, respectively
5. The drift for various damage states increased when H/t ratio increased. On the contrary, the drift for various damage states decreased while the skew angle increased. Further, a wide drift range of damage state response was observed for H/t ratio and skew angle. The reason for this trend is the contribution from other main factor are important that affected on the performance drift of SMA-RC wall bridge pier.

Since the present study considered the effect of main factors on the performance damage states, further study for interaction of each factor should be conducted for better understanding. Moreover, a part of this results may useful as a basic understanding the important of design parameters to optimize the drift level of damage state for concrete wall bridge pier using SMA. Thus, enhancing the seismic performance of bridge system.

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