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A Damage Index for Assessing Seismic-Resistant Designs of Masonry Wall Buildings Reinforced with X-Bracing Concrete Frames

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Abstract: In this paper, a suitable damage index is demonstrated to assess the seismic-resistant design of masonry wall buildings reinforced with double x-bracing concrete frames. As a criterion indicative of the damage level that might occur after an earthquake, the damage index can be calculated by using analytic results, by using the Park–Ang formula on masonry wall buildings reinforced with concrete structures, and by adjusting the index values in accordance with the results of the analysed models. The data used in this study are collected from the results of four-storey concrete structures with masonry walls under cyclical lateral forces. To simulate the masonry walls' structural behaviours for damage assessment, x-bracings placed as crosses on each bracing are used to support the compressive strength. Then, the analysis results are used to assess the damage that occurs to the masonry wall building structure by considering deformation and energy decay; additionally, a suitable damage index is calculated for each damage level. The damage index can be considered in the seismic-resistant design of masonry walls reinforced with x-bracing concrete frames.

Keywords: damage index; masonry wall; cyclic load; equivalent strut

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1. Introduction

An earthquake is a force that occurs in the horizontal direction and spreads to every floor of a structure. Moreover, earthquakes damage the masonry walls of reinforced concrete buildings. This damage affects the safety of the people in the building. For that reason, there are many studies on the evaluation of the damage levels of structures under earthquake forces to reduce disaster losses. In Thailand, there is a risk of earthquakes. The most damaged buildings are small- and medium-sized buildings, such as residential houses, commercial buildings, and school buildings. In addition, masonry is used to build partition walls in these buildings [1].

Masonry walls are parts of buildings that are essential for their behaviours under active forces from earthquakes. Most structural masonry buildings in Thailand feature walls built using antique masonry and block masonry. These techniques are used to support the weight of the beams, floors, and roofs, which are constructed with other materials, such as wood and steel. Most of the destruction to structural masonry buildings in Thailand results from the buildings leaning away from the masonry walls' planes. The damage in the beginning appears as diagonal cracking of the wall caused by the initial vibration force. If the force is severe, the cracking of the wall occurs. Finally, the wall cannot stand as usual, and it is destroyed. In brief, the damage that occurs to the wall interacts with the building frame when the building moves under an earthquake force. The level of damage can be evaluated using a structural analysis if appropriate models and criteria are used.

This research shows an appropriate damage index definition for the damage assessment of masonry wall buildings reinforced with x-bracing concrete frames; these frames are used as indicative criteria of the damage level that might occur under an earthquake force. The damage index can be calculated by using analytical results, by using the Park–Ang formula on models of masonry wall buildings reinforced with concrete structures, and by adjusting the index values in accordance with the results of the analysed models [2].

2. Literature Review

2.1. Park–Ang Damage Index

The damage index is a criterion for quantitatively measuring damage. Additionally, the index suggests that a structure has an external force acting on it that leads to damage, such as earthquake and lateral forces. The index can be used to assess the damage by determining the level of damage. Generally, the damage index is defined as a value. If the value is equal to 0, no damage occurs. If the value is equal 1, high-to-extreme damage occurs. In this research, the Park–Ang damage index is used to evaluate the damage levels of masonry wall buildings. The total damage caused by inelastic deflection and the damage due to energy collapse in the structure from back-and-forth responses are shown. The damage index is written as the following equation [2]:

$$DI = \frac{\delta_M}{\delta_u} + \frac{\beta}{Q_y \delta_u} E \tag{1}$$

where
δ_M is the deformation value after alternating the building force.
δ_u is the maximum deformation capacity value under unidirectional force before a disaster.
β is a coefficient in the relationship between the damage level and accumulated energy, with its value depending on the type of building being analysed.
Q_y is the strength at the yield point of the building.
E is the accumulated energy under the reverse action force.

The displacement value δ_M and accumulated energy value under the reverse action force E can be analysed by using this model under an earthquake force; the model considers the maximum deformation capacity value δ_u, and the coefficient β depends on the type of building being analysed. This coefficient is calibrated with values from laboratory experiments.

2.2. Structural Analysis of Model of Masonry Wall Building Reinforced with X-Bracing Concrete Frame

The deformation value and accumulated energy value under the reverse action force in Equation (1) can be determined by analysing the building structure under an earthquake force, which is examined by using an appropriate model. A masonry wall is modelled by using a multiple-strut model. For masonry walls within reinforced concrete building frames with an equivalent x-bracing form; the diagonal compressive strength is obtained as shown in Figure 1A. This paper investigates the response of masonry wall buildings subjected to horizontal forces. The structural behaviour of the walls is represented through x-braces, modelled according to the approach proposed by Saneinejad and Hobbs (1995). The damage index proposed by Park and Ang is adopted to examine the damage level of the masonry walls, and an infilled RC frame is designed and used as a case study. The cross symbol on the first bracing is between the corner of the beam and the column. Furthermore, the bracing model is defined by concrete section elements, with relational values between the stress and strain, reducing the lateral force, as shown in Figure 1B.

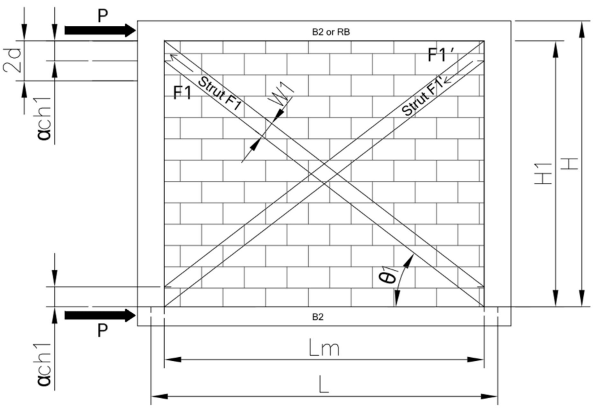
The stress–strain relationship of the model is defined by four parameters: peak strength (f_{mi}), peak strain (ε_{mi}), residual strength (f_{mri}), and residual strain (ε_{mri}). These parameters can be obtained from equations calibrated with values from laboratory experiments. The cross-sectional size of the bracing that determines whether the thickness is equal to the actual thickness of the original wall (t_w) and the effective width is equal to $0.7a$ in Equation (2) or W1 in Equation (4). According to α, the regulation from the DPT standard 1301/1302-61 [3] is as follows:

$$a = 0.175(\gamma_1 h_{col})^{-0.4} + \gamma_{inf} \tag{2}$$

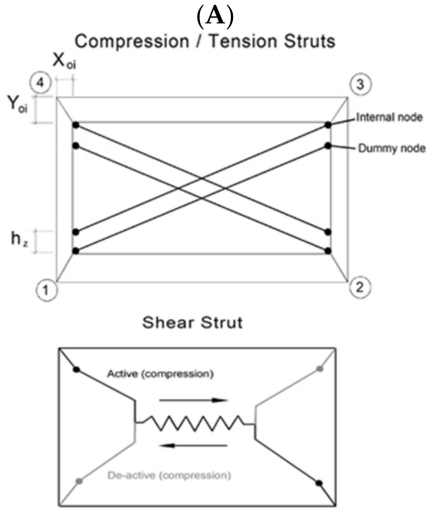
where h_{col} is the height of the column measured from the base of the pole to the centre point of the beam, r_{inf} is the diagonal length of the masonry wall, and γ_1 is a coefficient used to find the equivalent bracing width of the masonry wall. Then, the equation can be written as follows:

$$\gamma_1 = [\frac{E_{me}t_{inf}\sin(2\theta)}{4E_{fe}I_{col}h_{inf}}]^{0.25} \quad (3)$$

where
E_{fe} is the modulus of elasticity of the rigid frame material.
E_{me} is the modulus of elasticity of the masonry wall material.
I_{col} is the moment of inertia of the column's cross-sectional area.
h_{inf} is the height of the masonry wall.
t_{inf} is the thickness of the masonry wall.
θ is the angle between the height and length of the masonry wall.



(**A**)



(**B**)

Figure 1. Model of masonry wall building reinforced with x-bracing frame. (**A**) Model of masonry wall building reinforced with x-bracing concrete frames for compressive strength. (**B**) Model of masonry wall building reinforced with x-bracing concrete frame for compression/tension and shear strut.

In addition, the compressive strength of the reinforced masonry wall f_m is proportional to the specific surface area of the masonry walls S_r and can be calculated from the relationship between f_m and S_r [4]. The width of the compressive strength W_1 is calculated from the touch surface length of the force unit, which can spread between the column and masonry wall [5], as follows:

$$W_1 = \alpha_c \frac{l_m}{\sqrt{h_1.^2 + l_m.^2}} = \alpha_c h_1 \cos\theta_1 \quad (4)$$

$$\alpha_c = \frac{1}{h}\sqrt{\frac{2M_{pj} + 2\beta_c M_{pc}}{\sigma_c.^t}} \quad (5)$$

$$\sigma_c = \alpha_c \frac{f_m}{\sqrt{1 + 3\mu^2 r^4}} \quad (6)$$

where
μ is the friction coefficient between the building frame and brick wall;
r is the ratio between the height and width of the building frame $(r = h/l)$;
β_c is the reduction factor of the pole $(\beta_c = 0.2)$.

2.3. Coefficient Calibration of the Relationship between the Damage Level and Energy Decay

As mentioned above, the coefficient is featured in the relationship between the damage level and accumulated energy. β depends on the type of building analysed, and it is calibrated with values from experiments with the analysis models. Moreover, an appropriate coefficient for masonry walls is found that samples the testing results from several previous studies and creates a model sample for testing by simulating x-bracing characteristics, as mentioned before.

Then, the analysis results are taken to assess the damage to the wall structure by considering the deformation value and energy decay and by adjusting the coefficient that relates the damage level to the accumulated energy to obtain a value that corresponds with the testing results.

2.4. Damage Index of Study Sample to Assess Seismic-Resistant Design of Masonry Wall Buildings

In this research, previous testing results are selected from various sources for study. Furthermore, these previous experimental results have a variety of designs. Some designs consider earthquake resistance and others do not. However, the various structural systems from the eight testing samples are as follows: Mehrabi's sample is a rigid frame and hollow block concrete brick wall [6], Wararuksajja's sample is an anti-bending frame and hollow block concrete brick wall [7], Jiang's sample is a lightweight brick anti-bending rigid frame [8], Morandi's sample is a hollow brick wall rigid frame [9], and Huang's sample is a brick wall and hollow block concrete rigid frame [10]. The size and detail characteristics of the model samples are shown in Figure 1 and Tables 1 and 2.

Table 1. Details of the model samples from the literature review.

Sample Name	H (mm)	L (mm)	D (mm)	W1 (mm)	t_w (m)
			Mehrabi et al. [6]		
No. 4	1537	2312	147	187	0.092
			Wararuksajja et al. [7]		
WS01	2800	4000	250	315	0.100
WS02	2800	4000	250	331	0.100
WS03	2800	4000	250	334	0.100
			Jiang et al. [8]		
AFKJ1	2950	5940	350	200	0.427

Table 1. *Cont.*

Sample Name	H (mm)	L (mm)	D (mm)	W1 (mm)	t_w (m)
		Morandi et al. [9]			
TA2	3125	4587	300	350	0.370
		Huang et al. [10]			
IF-1	1375	2250	218	120	0.200
IF-2	1375	2250	218	180	0.204

Table 2. Mechanical properties of the reinforcement x-bracing concrete frames used in the model samples from the literature review.

Sample Name	Maximum Compressive Strength (Mpa)	Pending Strength (Mpa)	Compressive Stress	Pending Stress (mm)
No. 4	5.5	0.19	0.0010	0.0060
WS01	9.4	0.20	0.0017	0.0050
WS02	7.8	0.20	0.0017	0.0050
WS03	6.8	0.20	0.0014	0.0018
AFKJ1	3.8	0.47	0.0016	0.0060
TA2	2.9	0.38	0.0011	0.0060
IF-1	5.4	0.22	0.0020	0.0090
IF-2	2.8	0.46	0.0014	0.0100

3. Structural Analysis of Reinforcement X-Bracing Concrete Frames Used in the Model Samples from the Literature Review

A masonry wall building is simulated according to an analysis of the models in each study by using the SeismoStruct 2023 program 3D model [11]. By simulating a masonry wall building reinforced with x-bracing concrete frames at the head of the columns with shear spring failure, each bracing property is determined regarding the masonry wall building failure behaviours from the experimental results of the analysed models. Then, the monotonic loading and cyclic loading characteristics of the deformed samples are analysed by defining displacement control according to the force pattern used to test each sample. Figure 2 shows a sample that defines the displacement value in the model [12–29]. Then, the analysis results are used to calculate and determine a suitable coefficient and damage index.

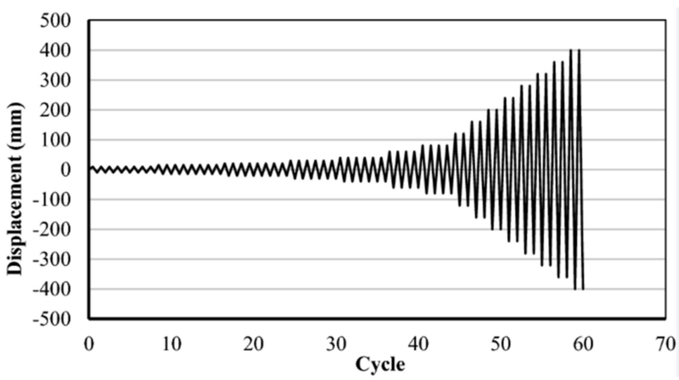


Figure 2. Monotonic loading and cyclic loading characteristics of the model samples [12–29].

The results of the analysis of the deformation behaviour are modelled. The results are shown in Figures 3 and 4, which show the relationship between the relative lateral displacement and lateral force of each model sample. In the figure, the lateral force continuously increases until structural failure occurs, and the maximum lateral force from the analysis is consistent with the testing results of the analysed models, as shown in Table 3.

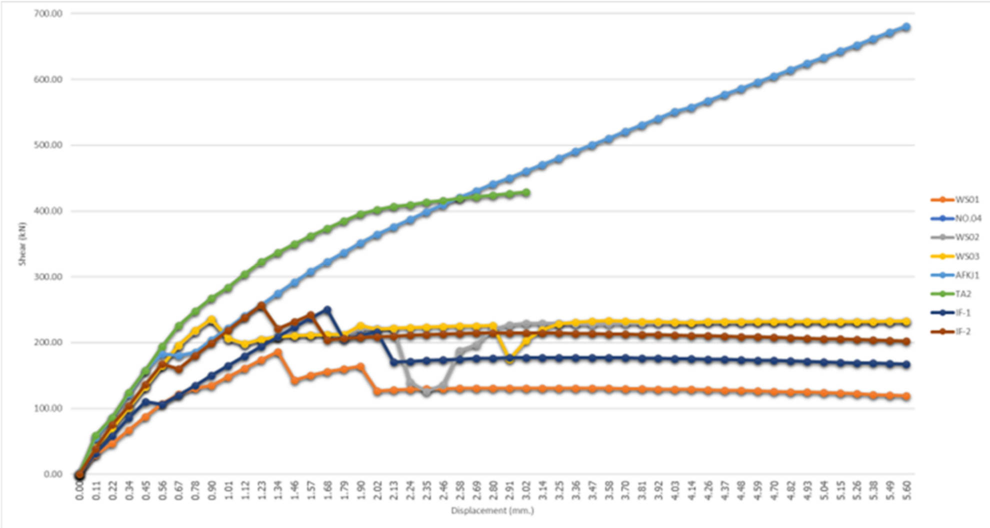
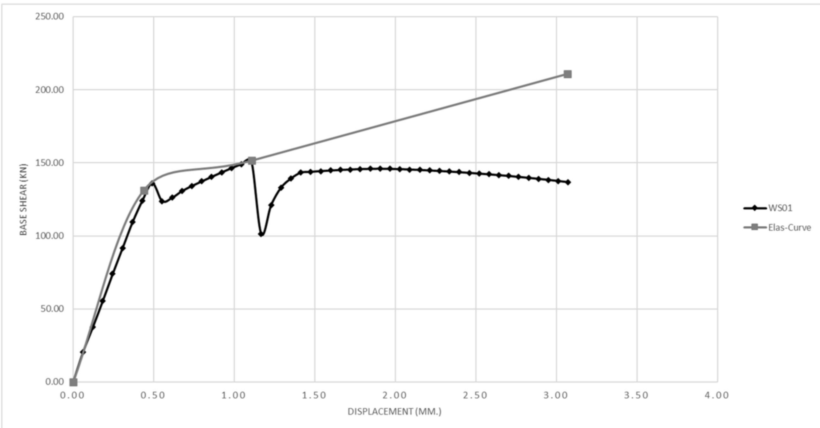
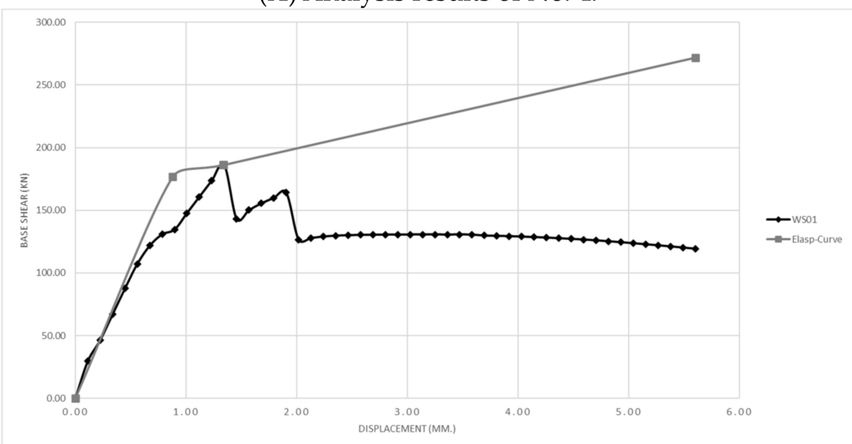


Figure 3. Relationship between the lateral force and lateral displacement of the model samples.

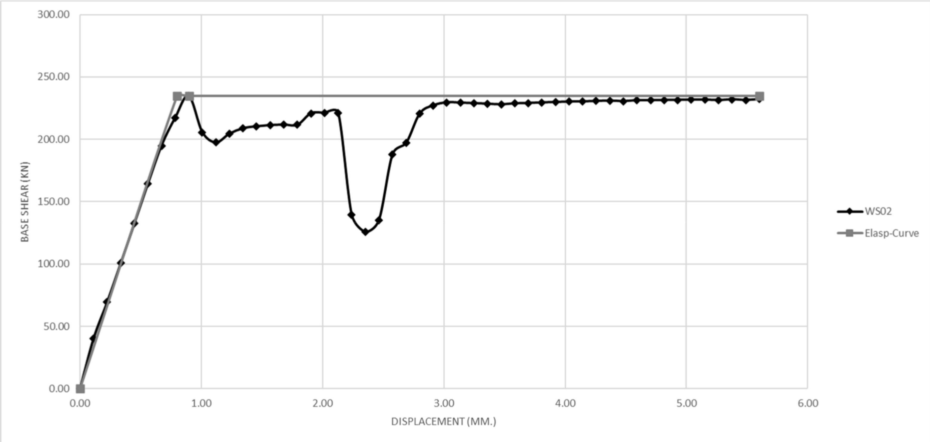


(**A**) Analysis results of No. 4.

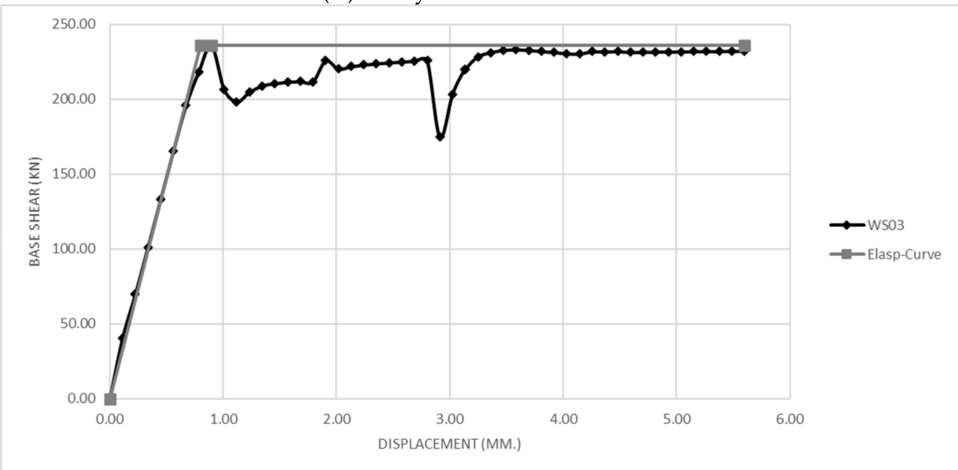


(**B**) Analysis results of WS01.

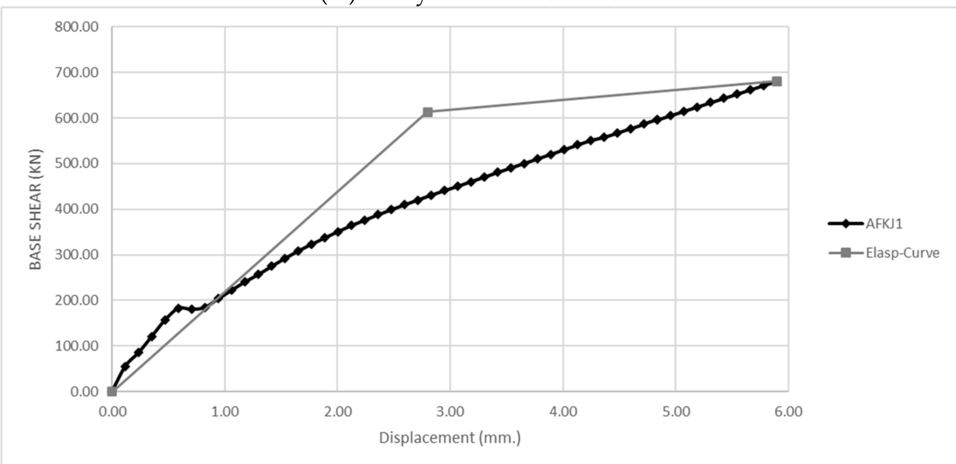
Figure 4. *Cont.*



(**C**) Analysis results of WS02.

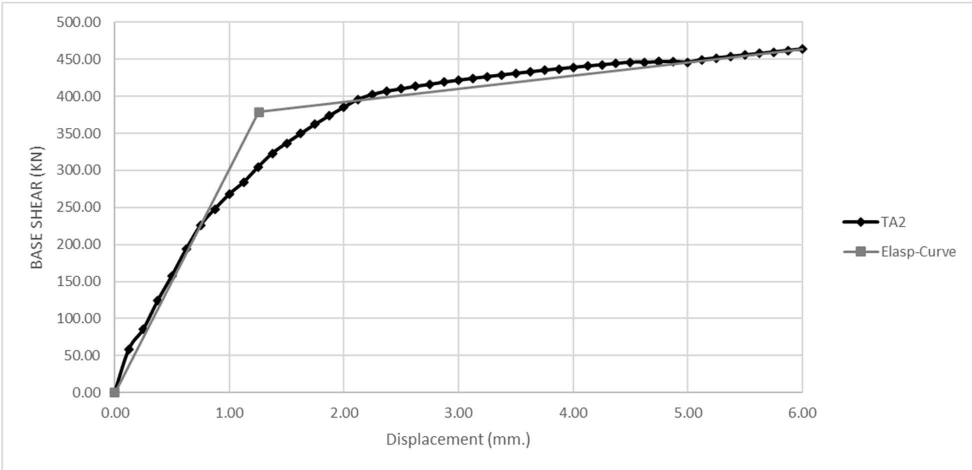


(**D**) Analysis results of WS03.

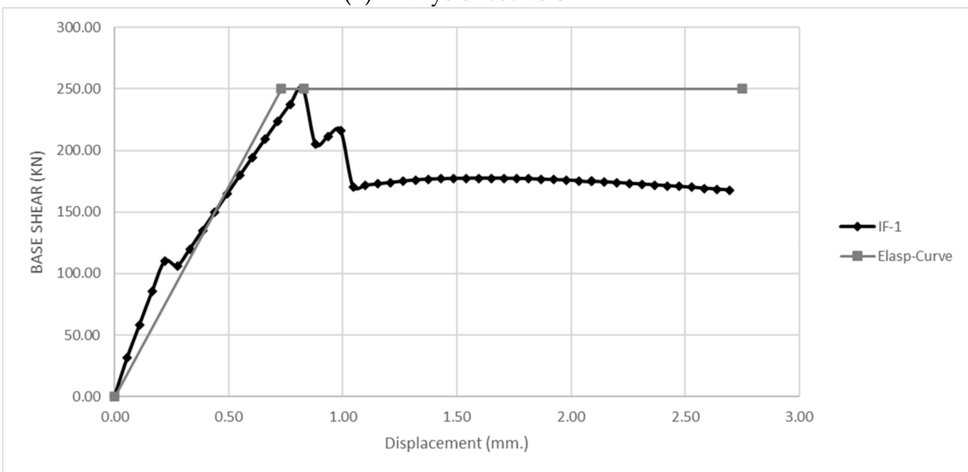


(**E**) Analysis results of AFKJ1.

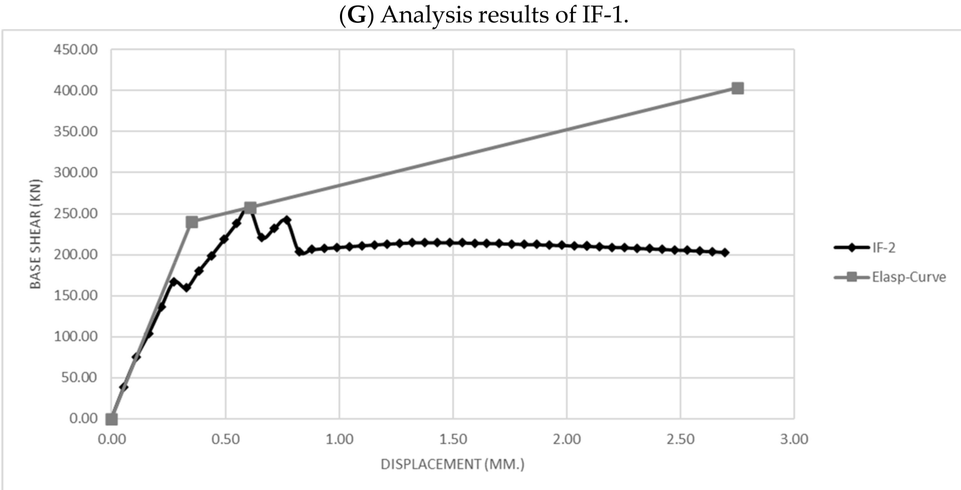
Figure 4. *Cont.*



(**F**) Analysis results of TA2.



(**G**) Analysis results of IF-1.



(**H**) Analysis results of IF-2.

Figure 4. Analysis results from alternating the lateral forces of the model samples.

Table 3. Maximum lateral force and maximum lateral displacement of the model samples (cyclic loading).

Sample	Load Target	Result Model Structure Analysis	
	Lateral Force (kN)	Maximum Lateral Force to Displacement (kN)	Maximum Lateral Displacement (mm)
No. 4	502.39	210.74	3.07
WS01	502.39	186.11	5.60
WS02	502.39	234.690	5.60
WS03	502.39	235.920	5.60
AFKJ1	502.39	613.140	5.90
TA2	502.39	378.470	6.25
IF-1	502.39	250.110	2.75
IF-2	502.39	239.860	2.75

3.1. Damage Index Calculation Used in the Structural Analysis of Model Samples from the Literature Review

The calculation of the damage index must involve variables obtained from the model's analysis. The variable values can be found as detailed below.

The accumulated energy under cyclic loading (E) calculated from the relationship between the lateral force and bracing axis deformation can be obtained from the area under compressive strength loading conditions, with two instances of bracing deformation under cyclic loading conditions. The energy is used to calculate the total accumulated energy of the masonry wall. The stress strength at yield point $\left(Q_y\right)$ is found from the lateral resistance of the x-bracing, and it is determined to be 70% of the maximum total resistance. The maximum deformation capacities under cyclic loading (δ_M) conditions from the analysis of structural deformation are found; the elements have two bracings under cyclic loading conditions at the maximum lateral displacement of each cycle. The value is defined as the damage index in the positive direction.

The maximum deformation capacity under monotonic loading (δ_u) has a value set to 1.25 times the deformation value at the destruction point, according to the model structure analysis results. The deformation value at the structural destruction point is defined as equal to the deformation value at the total strength, which is 25% of the reduction from the maximum strength. Results of model samples of masonry wall buildings reinforced with x-bracing concrete frames as shown in Table 4.

Table 4. Results of model samples of masonry wall buildings reinforced with x-bracing concrete frames.

Sample Name	Q_y (kN)	δ_M (m)	δ_u (m)
No. 4	151.48	0.0111	0.014
WS01	186.11	0.0134	0.017
WS02	234.69	0.009	0.011
WS03	235.92	0.009	0.011
AFKJ1	680.86	0.059	0.074
TA2	467.93	0.0625	0.078
IF-1	250.11	0.0083	0.010
IF-2	257.22	0.0061	0.008

The correlation coefficient between the damage level and accumulated energy (β) is optimized by adjusting the coefficient of determination from 0.10 to 0.35 and by calculating the damage index from the failure point. Then, a damage index value is obtained that is different for each model sample. For the optimization of a suitable coefficient, statistical calculations are used to determine an average damage index from the samples. Table 5 shows the damage index values calculated from each masonry wall building reinforced with x-bracing concrete frames, and the average damage index of the sample of masonry wall buildings reinforced with x-bracing concrete frames indicates the failure point. By using other coefficient values in the table, the appropriate coefficient is found to be 0.10–0.35. The coefficient can be used to calculate the average damage index; this is equal to 0.935 at the destruction point, which is close to 1.00.

Table 5. Damage index (DI) using various coefficients (β) of the model samples.

Sample Name	β					
	0.10	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**
No. 4	0.818	0.837	0.846	0.846	0.855	0.864
WS01	0.818	0.836	0.845	0.845	0.854	0.863
WS02	0.810	0.819	0.824	0.824	0.829	0.834
WS03	0.810	0.819	0.824	0.824	0.829	0.833
AFKJ1	0.822	0.843	0.854	0.854	0.865	0.876
TA2	0.833	0.867	0.883	0.883	0.900	0.917
IF-1	0.808	0.817	0.821	0.821	0.825	0.829
IF-2	0.806	0.812	0.815	0.815	0.818	0.821
Average	0.816	0.831	0.839	0.839	0.847	0.855
SD.	0.009	0.018	0.023	0.023	0.027	0.032
Avg. + SD.	0.825	0.849	0.862	0.862	0.874	0.887
Avg. − SD.	0.806	0.813	0.816	0.816	0.819	0.823

3.2. Determination of Damage Level for Assessing Seismic-Resistant Design of Masonry Wall Buildings

The appropriate coefficient DI is equal to 0.24. Therefore, this coefficient is used to calculate the damage indices at various levels of deformation of the model sample as a guideline to indicate the level of damage that may occur. The damage index calculation results of the three experimental samples used in Wararuksajja's research, namely WS01, WS02, and WS03, which provide the damage index at various damage points, are shown in Table 6. The characteristics of masonry wall damage from the test and damage index, which can define criteria for determining the damage level in four sessions, are shown in Table 7.

Table 6. Damage index at each damage level.

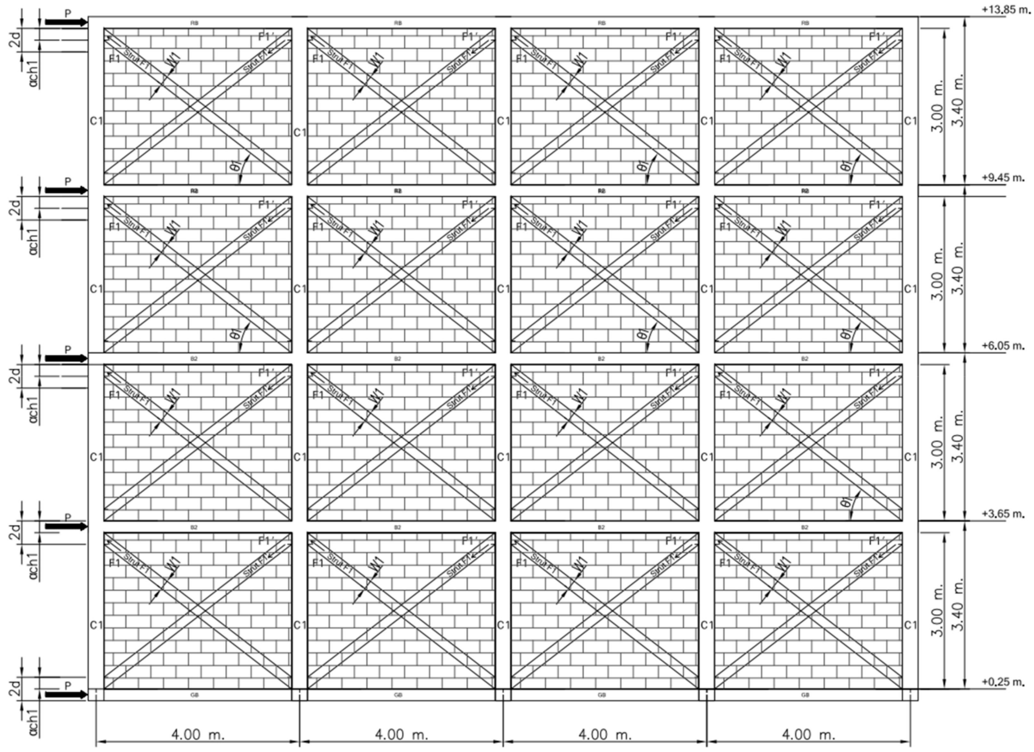
Damage Characteristics	Damage Index (DI)		
	WS01	**WS02**	**WS03**
Total collapse of infill	1.57	1.52	1.16
Extensive large cracks	1.07	1.03	0.84
Corner crushing	0.77	0.74	0.52
First diagonal crack	0.48	0.47	0.24

Table 7. Criteria for determining the level of Park–Ang damage index.

Damage Level	Physical Characteristics	Damage Index
Collapse	Total collapse of infill	>1.00
Severe	Extensive large cracks	0.80–1.00
Moderate	Corner crushing	0.50–0.80
Minor	First diagonal crack	0.25–0.50

4. Case Study of Masonry Wall Building Reinforced with X-Bracing Concrete Frames

A reinforced rigid frame model is shown in Figure 5A. The columns were reinforced with steel bars and the x-bracing concrete frame technique, because the shear strength acts on columns in buildings. The beams were reinforced with steel bars, as shown in Table 8. This is equivalent to using plastic hinges, which may be placed at the end of beams.



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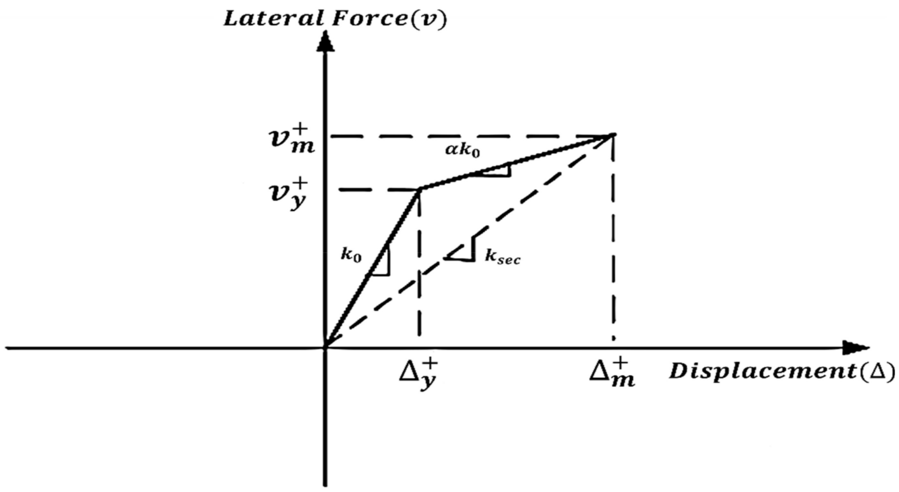


(**B**)

Figure 5. Part of the wall frame model. (**A**) An analytical model of the masonry walls according to the equivalent compressive x-brace concrete frame method. (**B**) Relation of the lateral force to the displacement value.

Table 8. The details of the reinforced steel bars.

Building	Size (mm.)	Main Reinforcement (mm.)	Stirrup Reinforcement (mm.)
C1	200 × 200	8DB16	RB6@150
B2	200 × 400	5DB16	RB6@150
RB	200 × 400	5DB16	RB6@150
W1	125 × 200	2RB9	RB6@150

The column's moment resistance (M_S) can be calculated from the sum of the original column's moment resistance (M_c) and the x-bracing concrete frames' moment resistance (M_B) as follows:

$$M_S = M_C + M_B \quad (7)$$

The x-bracing concrete frames' moment resistance (M_B) can be calculated from the sum of the concrete brace moment resistance and the steel bar moment resistance as follows:

$$M_B = \sum_{i=1}^{n} \left(f_{ys} (S_s) i_i \right) + \sum_{i=1}^{n} \left(f\prime_c (S_c) i_i \right) \quad (8)$$

where
fys and *f′c* = yield the strength of the steel bar and compressive strength of the concrete brace;
Ss and *Sc* = cross-section of the steel bar and concrete brace;
V_{BF} = lateral load resistance of the reinforced rigid frame.

$$V_{BF} = 2(Mpj + Ms)/h = 2(Mpj + Mc + Mb)/h \quad (9)$$

where M_{pj} = the joint connecting plastic moment, which is considered to include the smallest moment of the column M_{pc} plastic moment, the beam M_{pb} plastic moment, and the joint connecting moment of the column–beam. The shear strength of the column V_C is half that of V_{BF}:

$$V_C = \left(M_{pj} + M_s \right)/h \quad (10)$$

Case Study of Masonry Wall Building Reinforced with X-Bracing Concrete Frames

The concrete building structure has a first floor level 0.25 m, and the building has a width of 4.00 m/bay, with four spaces; a height of 13.85 m; a general floor thickness of 0.10 m; and a live load of 3.00 kN/m^2. Moreover, the front of the building frame, as shown in Figure 5A, consists of masonry walls, with the width of the entrance being equal to the column spacing and cross-sectional dimensions. The details of the reinforced steel bars of the columns and beams are shown in Table 8. The compressive strength of the cylinder concrete is 24 MPa, and the tensile strength of the reinforced steel bars is 400 MPa. An analytical model of a masonry wall building reinforced with x-bracing concrete frames is used with the equivalent compressive bracing frame method. Here, the width of the diagonal compressive strength of the masonry wall is W_1. Moreover, the diagonal compressive strength of the masonry wall is the lateral force resistance of the wall, which can be written in a graph expressing the relation of the lateral force to the displacement value, as shown in Figure 5B. When v_m^+, v_y^+, Δ_m^+, and Δ_y^+ are the maximum resistance, resistance at the yield point, maximum movement, and movement at the yield point in the direction of the acting force, K_0 and K_{sec} are the initial stiffness value and cross-sectional stiffness value, respectively.

The maximum resistance of the compressive strength V_m of the masonry wall building reinforced with x-bracing concrete frames can be calculated as

$$V_m = f_1 \cos\theta_1 + f_1' \, cos\theta 1 = 2W_1 t f_a \cos\theta_1 \quad (11)$$

where
f_a is the allowable compressive stress of the masonry wall prism, $f_a = 0.6\varnothing f_m$;
f_m is the maximum compression of the masonry wall prism;
$\varnothing$ = 0.65, and t = the thickness of the masonry wall;
θ_1 is the tilt angle of the diagonal compressive strength of the masonry wall.

The balance of the lateral force P is equal to the sum of the resistance frame and compressive strength f_1, f_1':

$$P = V_{BF} + f_1 \cos\theta_1 + f_1' \cos\theta_1 \quad (12)$$

$$P = V_{BF} + 2W_1 t f_a \cos\theta_1 \quad (13)$$

The reinforced concrete building's rigid frame was calculated and designed for seismic resistance. We calculated the concrete building structure using a computer design in the SeismoStruct 2023 program to identify the requirements for the seismic resistance of the concrete building frame using the nonlinear static force method (a pushover analysis) with response spectrum acceleration. The building was located in Chiang Rai Province (DPT Standard 1301/1302-61) [3]. The lateral force base shear of the concrete building's rigid frame design was 502.39 kN, and the code used for the lateral displacement safety factor was ASCE41-17 [30]. For the reinforced design of the rigid frame, with steel bars along the length of the columns, to reinforce the beams along their length, the size of the main reinforcement was DB16, and the size of the stirrup reinforcement was RB6; the size of the main reinforcement of the steel bars of the x-bracing concrete frames was RB9, and the size of the stirrup reinforcement was RB6 at the end and base of the columns, spanning a length 2.0 times that of the beams' depth. The parts of the masonry walls using x-bracing concrete frames are shown in Figure 6.

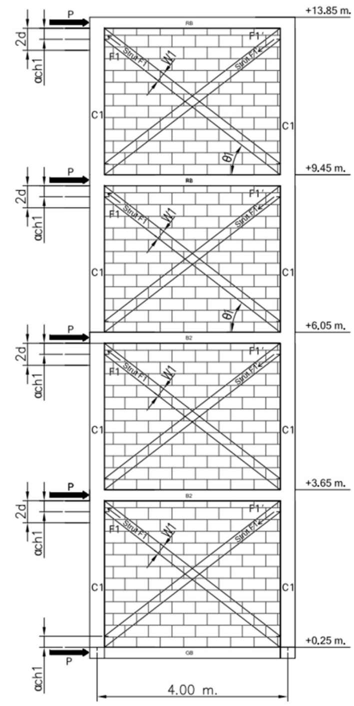
The moment resistance and shear resistance of the original column were compared with those of the reinforced column, and they were calculated using Equations (7), (8), and (10), as shown in Table 9. Here, V_c is the value of the resistance of a single column. The resistance of the reinforced x-bracing concrete frames in the masonry walls of the building can be calculated using Equations (7)–(13), as shown in Table 10, where the P value is the resistance of a single span of the case study concrete building structure, as shown in Figure 6A. The design lateral force, which we also calculated for the four-storey concrete building structure, was 502.39 kN for both the original wall structure and reinforced x-bracing structure.

Table 9. Resistance of the column of the masonry wall building reinforced with x-bracing concrete frames.

Parameter	Original Column	Reinforced X-Brace Concrete Frames
M_c (kNm)	30.05	30.05
M_b (kNm)	-	518.00
M_S (kNm)	-	548.05
M_{pj} (kNm)	23.65	23.65
V_c (kNm)	11.19	190.57

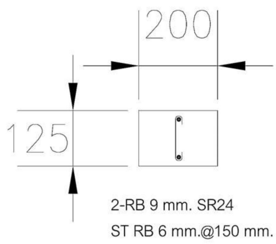
Table 10. Resistance of the masonry wall building reinforced with x-bracing concrete frames.

Parameter	Original Walls	Reinforced X-Brace Concrete Frames
α_c	0.085	0.1176
W_1 (mm)	-	124.26
$2W_1 tfa \cos\theta_1$ (kN)	-	75.52
V_{BF} (kN)	22.38	155.79
P (kN)	22.38	231.31
$Design\ lateral\ force$ (kN)	502.39	502.39



(**A**)

(**B**)



(**C**)

Figure 6. Masonry walls, columns, and beams reinforced with x-bracing concrete frame. (**A**) Single-span reinforced building frame; (**B**) cross-section of the reinforced column and beam; (**C**) cross-section of the reinforced x-bracing concrete frame.

5. Analysis of Masonry Wall Building Reinforced with X-Bracing Concrete Frames

For the four-storey concrete building structure, as shown in Figure 5A, we created a model for a structural analysis using the SeismoStruct 2023 program 3D model, as shown in Figure 6. The data used for the structural analysis of the masonry wall building reinforced with x-bracing concrete frames are shown in Tables 9 and 10. The moment resistance of the columns and lateral force resistance of the walls were calculated, as shown in Equations (1)–(13).

An analysis of structure of the four-storey masonry wall building reinforced with x-bracing concrete frames was performed using the nonlinear static force method (pushover analysis method), calculating the target storey drift value (δ_t) with the DPT Standard 1301/1302-61. We used response spectrum acceleration for the building, which was located in Chiang Rai Province. The target design storey's drift value δ_u was increased by 1.25 times $(1.25\delta_m)$ to assess the damage index (DI). The parameter results of the target storey's drift value (β) equalled 0.1–0.35, as shown in Table 11.

Table 11. Results of masonry walls with and without x-bracing concrete frames used in the four-storey concrete building structure models.

Case Study				β					
	Q_y (kN)	**δ_M (m)**	**δ_u (m)**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**
Four-storey concrete building with x-bracing concrete frames	478.780	0.048	0.06	0.83	0.85	0.86	0.86	0.88	0.89
Four-storey concrete building without x-bracing concrete frames	67.160	0.240	0.30	1.69	2.59	3.03	3.03	3.48	3.93

Figure 7 shows the maximum lateral force and maximum lateral displacement of the four-storey concrete building structure with masonry walls reinforced with x-bracing concrete frames; when the lateral force is 478.78 kN, the initial starting point of the lateral displacement is equal to 4.80 mm, and the yield maximum lateral displacement is approximately 24.00 mm. The results of the model structure analysis are shown in Table 11. The damage index (DI) indicates extensive large cracks, but the original walls without x-bracing concrete frames show a damage index criterion of more than 1.0, as shown in Table 7.

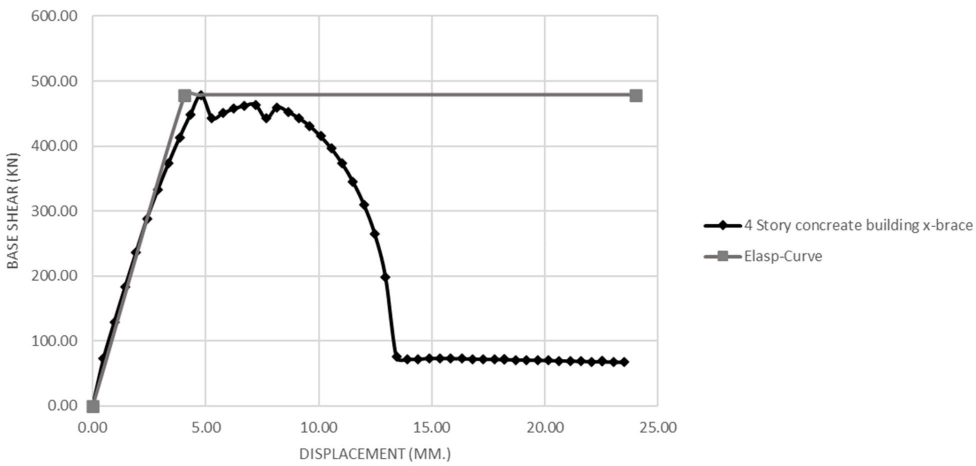


Figure 7. Model of masonry wall building reinforced with x-bracing concrete frame.

In Figure 8, we can see that the masonry wall building reinforced with x-bracing concrete frames resists higher maximum lateral force and yield lateral displacement values than the original walls without x-bracing concrete frames. For the original wall without x-bracing concrete frames, when the lateral force is 67.16 kN, the initial starting point of the lateral displacement is equal to 14.99 mm. By comparison, the structure reinforced with x-bracing concrete frames resists a higher lateral force value than the original wall without an x-bracing concrete frame structure, with an approximately 7.13 times difference in lateral forces.

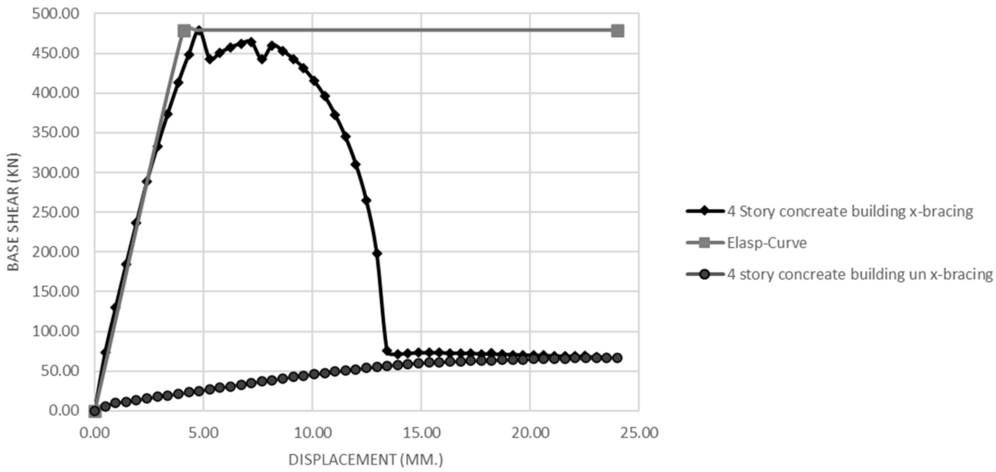


Figure 8. Comparison between masonry wall building with x-bracing and original wall building without x-bracing concrete frame.

6. Conclusions

In this study, a suitable damage index is determined. Masonry wall buildings reinforced with x-bracing concrete frames are assessed by analysing various models to study the damage behaviours under monotonic loading and cyclic loading conditions. Results, the case study demonstrates that the masonry wall building, reinforced with x-bracing concrete frames, exhibits enhanced seismic resistance, reduced potential for severe damage, and improved overall structural performance compared to the original structure. The detailed analysis and calculations support the effectiveness of x-bracing in mitigating the impact of seismic forces will affect to building collapse. The study results are summarized in the following main points:

1. The monotonic loading and cyclic loading conditions are analysed at the maximum lateral force. The analysis reveals that the results are consistent in the same direction and with the model structure analysis results.
2. The correlation coefficient between the damage level and accumulated energy (β) is appropriate for use in the calculation of the damage index using the Park–Ang equation. The Park–Ang equation for a masonry wall building (β) is equal to 0.10–0.35.
3. The criteria for the consideration of the damage level are defined as follows: when the damage index is between 0.25 and 0.50, the specimen has a minor damage level; when the damage index is between 0.50 and 0.80, the specimen has a moderate damage level; when the damage index is between 0.80 and 1.00, the specimen has a severe damage level; and when the damage index is more than 1.00, the specimen has a collapse damage level, resulting in the structure of the building experiencing a disaster.
4. The damage index for assessing the seismic-resistant design of masonry wall buildings reinforced with x-bracing concrete frames shows that they resist higher lateral force base shear values before lateral displacement than the original walls without x-bracing concrete frame structures, with values of 478.78 kN and at 67.16 kN, respectively, demonstrating an approximately 7.13 times difference in lateral forces. The masonry wall buildings reinforced with x-bracing concrete frames show extensive large cracks, and the damage index criterion (DI) is equal to 0.8 in the maximum lateral force base shear design.

Therefore, the use of reinforced x-bracing concrete frames in masonry wall buildings offers a holistic approach to seismic resistance. This strategy addresses the vulnerabilities of traditional masonry structures, providing improved stability, increased shear strength, controlled de-formation, and enhanced energy dissipation. The adaptability of x-bracing systems makes them valuable not only in new construction but also in retrofitting existing buildings for better seismic performance.

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