Polyurea Retrofit Material Development and Evaluation of Polyurea Repaired and Strengthened Performance of Masonry Structures

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Profile

Education

- 2011-2016 Yonsei Univ., Dept. of Civil Eng.
- 2016-Present Yonsei Univ., Graduate School (Combined Master and Doctoral Degree)

Research Output

Catergory	Published
1. International Journal	10
2. Domestic Journal	7
3. International Proceeding	4
4. Domestic Proceeding	32
Total	53

Research Area

- Polyurea retrofitting
- Structure strengthening
- FRP rebar
- Polyurea material
- FRP strengthening
- Numerical analysis of structures

Related works

➢ International Journal

Author	Year	Title	Journal	Vol.	PP
Tae-Hee Lee, Seung-Jai Choi, Dal-Hun Yang, Jang-Ho Jay Kim	2022	Experimental Seismic Structural Performance Evaluations of RC Columns Strengthened by Stiff-Type Polyurea	International Journal of Concrete Structures and Materials	16	1-28
Tae-Hee Lee, Jun-Hee Park, Dal-Hun Yang, Jang-Ho Jay Kim, Norhazilan Bin Md. Noor	2022	Material Enhancements of Newly Developed Stiff Type Polyurea for Retrofitting Concrete Structures	Case Studies in Construction Materials	17	e01431

➢ Domestic Proceeding

Author	Yea r	Title	Journal	PP
양성준, 남연우, 한태훈, 이태희, 김장호	2021	폴리우레아와 GFRP로 표면 보강한 조적 벽체의 내진 성능 시험	한국콘크리트학회 학술대회 논문집	139 – 140
한수호, 이태희, 양성준, 김장호	2021	내진 보수보강용 폴리우레아를 표면 보강한 조적 벽체의 내진 성능 시험	한국콘크리트학회 학술대회 논문집	125-126
방준희, 이태희, 양달훈, 박준희, 김장호	2020	조적식 구조물 내진 보수보강용 폴리우레아를 도포한 원형공시체 탄산화 노출 시험 평가	대한토목학회 학술대회	1065-1066
김장호, 한수호, 윤도균, 이태희	2020	내진 보수보강용 폴리우레아 개발 및 조적식 부재의 사인장 강도 평가	한국구조물진단유지관리공학회 학술발표회 논문집	117
양달훈, 이태희, 조용인, 김장호	2019	조적식 구조물 내진 보수보강용 폴리우레아의 재료성능 평가	한국콘크리트학회 학술대회 논문집	401 – 402

Overview of Thesis

Chapter 1 **Introduction**

Chapter 2 **Backgrounds and literature reviews**

Chapter 3 **Polyurea material development**

Tae-Hee Lee., Jun-Hee Park, Dal-Hun Yang, Jang-Ho Jay Kim, Norhazilan Bin Md. Noor (2022), "*Material Enhancements of Newly Developed Stiff Type Polyurea for Retrofitting Concrete Structures*", ***Case Studies in Construction Materials,***(Published)

Tae-Hee Lee., Seung-Jai Choi, Dal Hun Yang, Jang-Ho Jay Kim (2022), "**Experimental Seismic Structural Performance Evaluations of RC Columns Strengthened by Stiff-Type Polyurea**", ***International Journal of Concrete Structures and Materials*** (Published)

Chapter 4 **STPU retrofit effect evaluation of repaired masonry wall**

Chapter 5 **Conclusions**

Contents

- Backgrounds and Objectives
- Polyurea Material development
- STPU Retrofit Effect Evaluation –Masonry wall-
- Conclusions

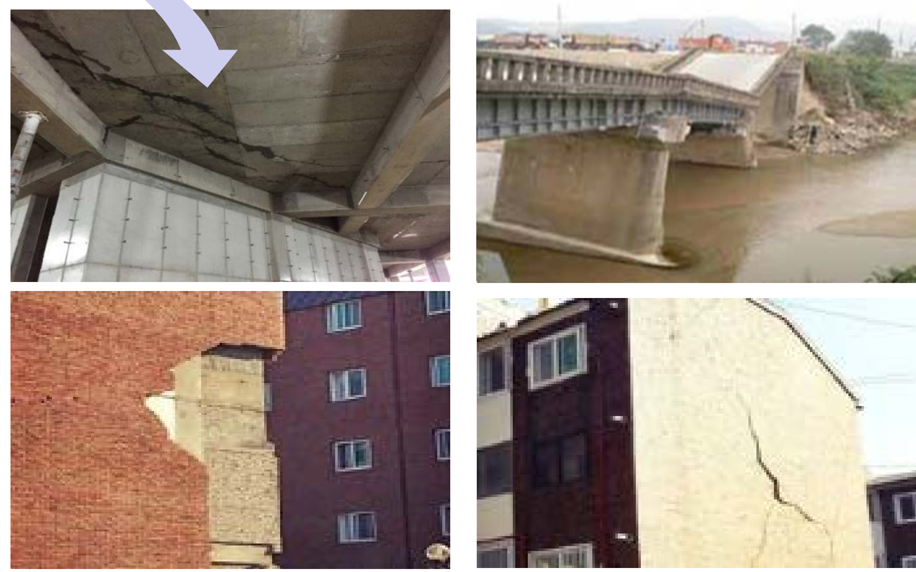
Backgrounds and Objectives

Backgrounds

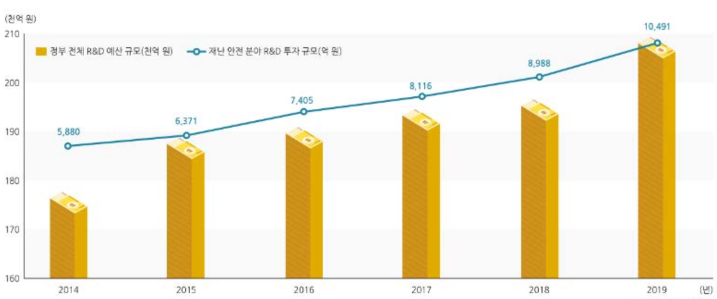
Old structures in Korea

- Old structures in Seoul

- Infrastructures are getting fragile due to aging



- R&D investment in structure's safety

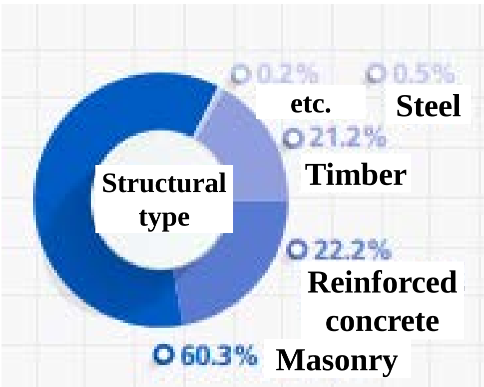


Need for structure strengthening and repairing

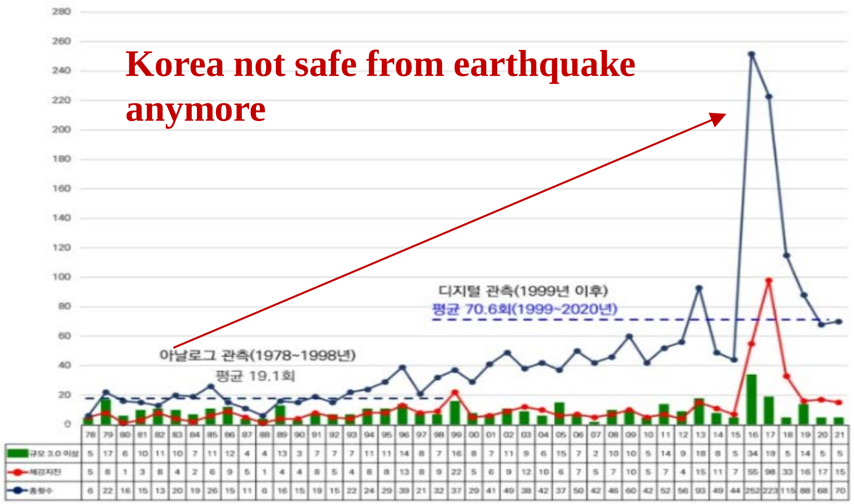
Backgrounds

Old structures in Korea

- Buildings over 30 years old in Seoul (SIT, 2020)



- Earthquake occurrence in Korea (KMA, 2022)



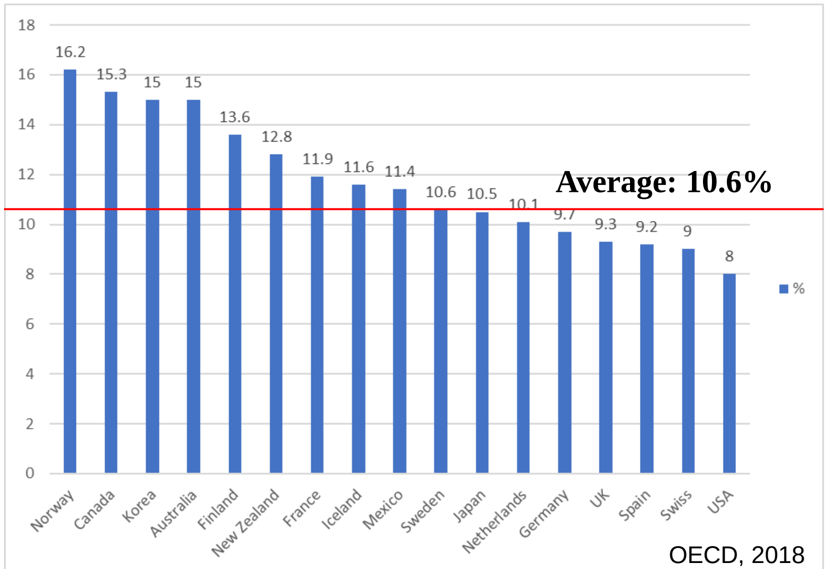
- Damaged masonry wall by seismic load

Need for developing economical and time-reducing strengthening method for masonry structure

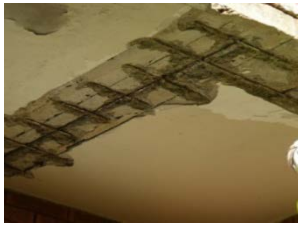
Backgrounds

Construction industry around the world

- Construction investment ratio to GDP in OECD countries



30% of construction investment for structures **maintenance**



- Structure damage due to environmental disaster

Earthquake

Tsunami

Hurricane

Sinkhole

Construction paradigm shifting

New construction ➡ Maintenance (repairing, strengthening…)

Backgrounds

Structure repairing and strengthening trend

- Structure strengthening using steel



High cost & Long construction time

- Structure strengthening using FRP



Epoxy bonding interface problem


Polyurea(PU) strengthening →

- No bonding interface
- Application by spray
- Short curing time
- High tensile strength

Backgrounds

Pros and Cons of polyurea retrofit

Pros

- Increase the flexural and shear strength of structure
- Increase the ductility and failure deformation of structure
- Energy dissipation
- Withstands extreme environments
- Low VOCs emission
- Easy to apply (spray coating, dries fast)

Cons

- High reactivity and quick-curing can cause poor adhesion
- For Experienced applicators only
- Surface problem (blistering, pinhole…) if the coating isn't properly mixed
- Low confinement effect
- Vulnerable to fire

Objectives

Development of new polyurea material

- Higher tensile strength and low percent elongation

Mechanical test

Durability test

Confinement effect

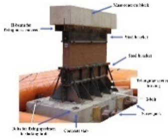
Strengthening effect

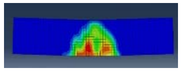
Newly developed **Stiff type polyurea(STPU)**

STPU retrofitting effect evaluation for masonry wall

Masonry wall

Experimental **Numerical**





Objectives

Reasons of using polyurea for strengthening structures

- Easy to apply(short curing time, no bonding interface, spray system)
- High strengthening effect(high tensile strength, high ductility)

Main objectives

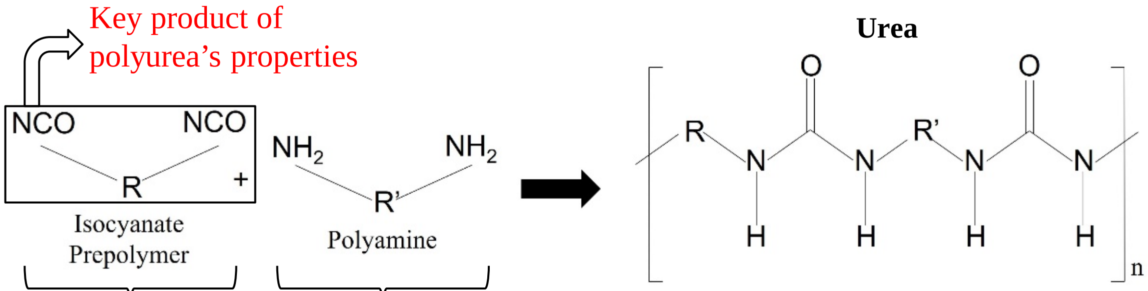
- Development of retrofitting material to meet the radically growing demand for structure strengthening due to aging of structures

- Evaluation of strengthening effect of newly developed material(STPU)

Polyurea Material Development

Developing STPU

Introduction of polyurea



Prepolymer (soft segment, soft domain)

Hardner (hard segment)

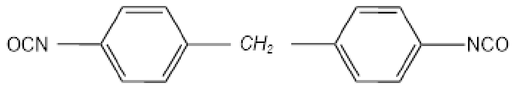
Chain form

Auto catalystic

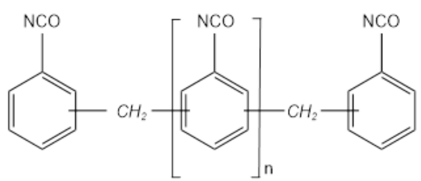
Non-byproduct

Existing flexible-type PU has low stiffness → Low load-carrying capacities, Low energy absorption capacities → Solution: Developing STPU

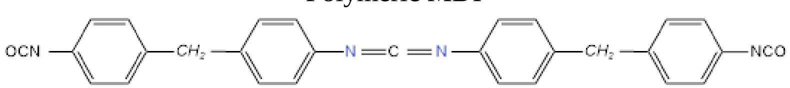
Developing STPU



Monomeric MDI



Polymeric MDI



Modified MDI

Properties	Monomeric MDI	Polymeric MDI	Modified MDI
Molecular weight	250.3	360~400	296
State at room temperature	Solid	Liquid	Liquid
Functional group	2	2.7	2
Color	White-Pale yellow	Brown	Light yellow
Gravity	1.19 at 40 ℃	1.24 at 40 ℃	1.21 at 40 ℃
Viscosity (cps at 25 ℃)	-	100~3,000	35~650

Developing STPU

Material composition of STPU

Material	Component		Case 1	Case 2	Case 3
			Weight [%]		
Prepolymer	Modified MDI	(P,P'- METHYLENE BISPHENYL ISOCYANATE)	-	42	-
	Monomeric MDI	(4,4'-Methylene diphenyl diisocyanate)	53	-	-
	Polymeric MDI	Methylenebis(4,1-phenylene)diisocyanate	-	10	64.50
	Polyol	Alpha-(2-aminomethylethyl)-omega-(2-aminomethylethoxy)-poly(oxy(methyl-1,2-ethanediyl))	27	39.50	27.50
		Polyoxypropylene glycol	19	-	5
	Additive	Propylene carbonate	1	8.50	3
Hardener	JEFFAMINE	Alpha-(2-aminomethylethyl)-omega-(2-aminomethylethoxy)-poly(oxy(methyl-1,2-ethanediyl))	72.1	70.1	24.6
		Poly[oxy(methyl-1,2-ethanediyl)],.alpha.,.alpha.',.alpha."-1,2,3-propanetriyltris[.omega.-(2-aminom,ethylethoxy)	-	9.0	-
	FUNCTIONAL AMINE	3,5 Diethyltoluene-2,4/2,6-diamine	25.9	15.4	11.9
		4,4'-Methylene bis[N-(1-methylpropyl) benzenamine	1.6%	5.0	32.6
		4,4'-Methylenebis(2-chloroaniline)	-	0.0	29.4
	UV additive (UV sorbent)	ZIKASORB-BS	0.5	0.5	1.5

STPU= High tensile strength
Relatively low percent enlongation

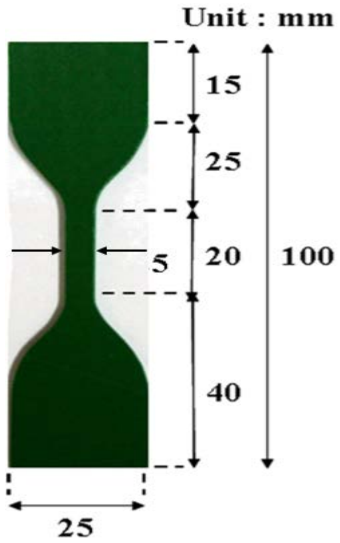
Case 1: Monomeric MDI
Case 2: Modified MDI
Case 3: Polymeric MDI

3 cases of NCO(%): 13, 15.5, 18 % → 9 cases

Mechanical Property Tests

Tensile strength and percent elongation test

- **Type 3 dumbbell specimen**



- **Test setup**

- Experiments followed **KS M 6518**
- The experiment used the universal testing machine (UTM)

$$T_B = F_B / A$$

T_B: tensile strength (MPa)
F_B: maximum load (N)
A: cross-sectional area of specimen(mm^2)

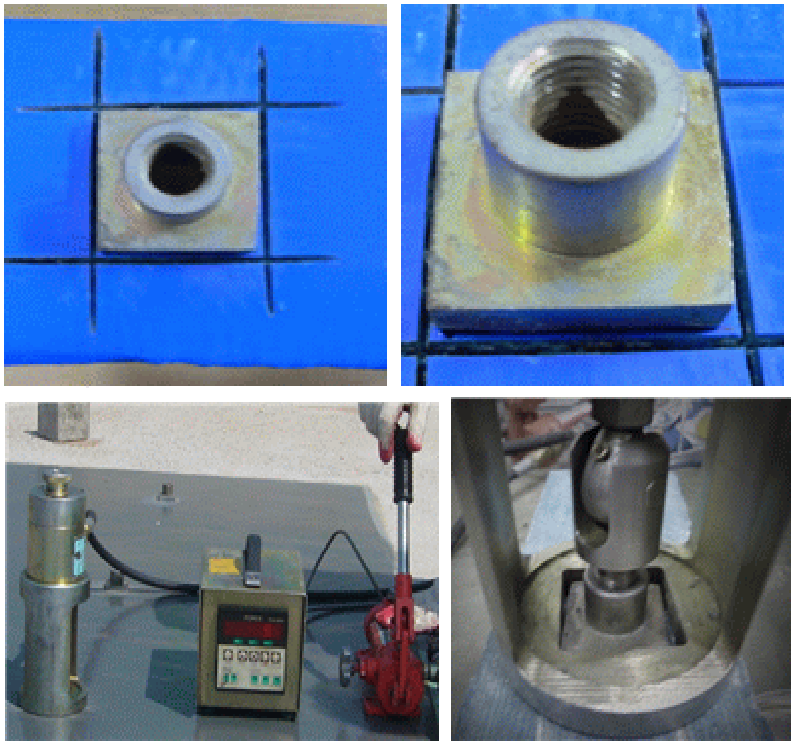
$$E_B = \frac{L_l - L_0}{L_0} \times 100$$

E_B: elongation at break
L_l: length at rupture (mm)
L_0: initial specimen length (mm)

Mechanical Property Tests

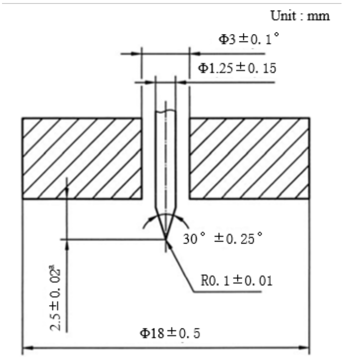
Bonding stress, shore hardness and drying time test

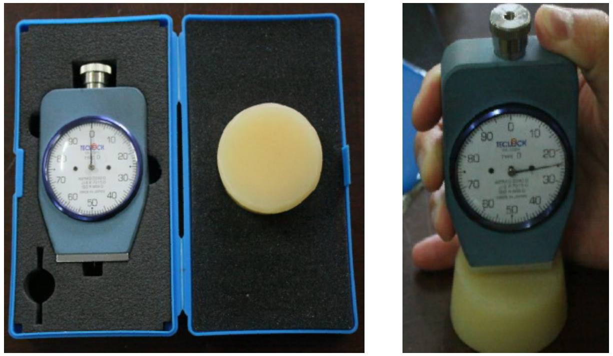
- **Pull-off test setup**



- Experiments followed **KS F 4922**

- **Shore D hardness test**



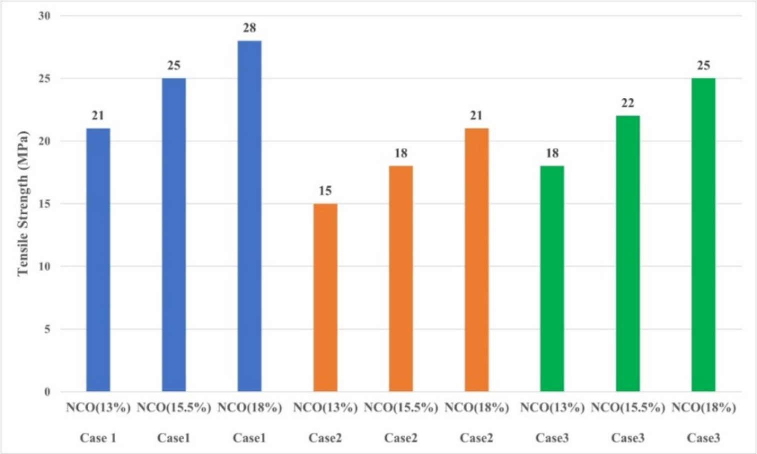


- Experiments followed **KS M ISO 7619-1**

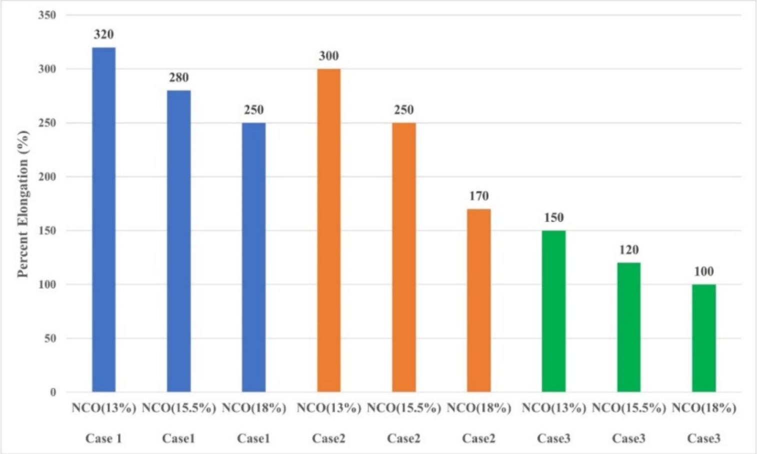
Mechanical Property Test Results

Tensile strength and percent elongation test results

▪ Tensile strength test results



▪ Percent elongation test results



▪ Tensile strength and percent elongation test results

	NCO [%]	Tensile strength [MPa]	Percent elongation [%]
Case 1	13	21	320
	15.5	25	280
	18	28	250
Case 2	13	15	300
	15.5	18	250
	18	21	170
Case 3	13	18	150
	15.5	22	120
	18	25	100

Low ductility

Elongation of degradated polyurea > 250 % (KS F 4922)

- Tensile strength: Case1 > Case3 > Case2
  18% > 15.5% > 13% (NCO(%))

- Percent elongation: Case1 > Case2 > Case3
  13% > 15.5% > 18% (NCO(%))

Mechanical Property Test Results

Bonding stress, shore hardness and drying time test results

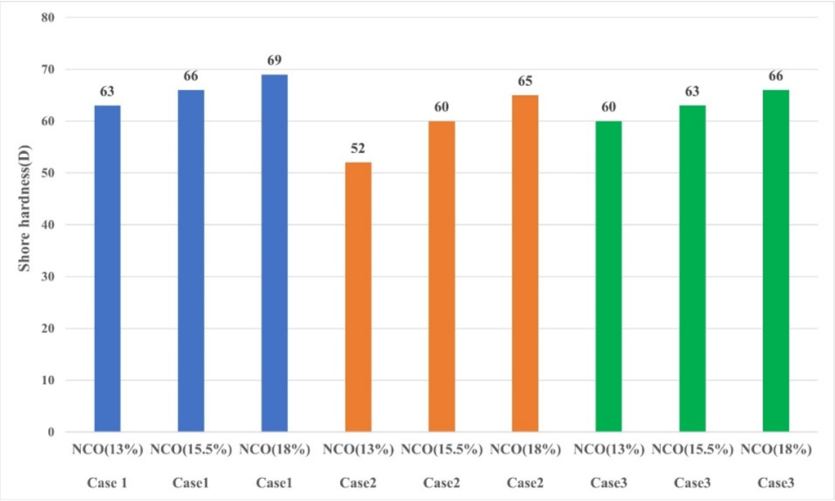
- **Bonding stress**

The PU bond strength requirement of Korean standard: 1.5MPa (KS F 4922)

All specimens: 1.5 ~ 2.5MPa

Standard was satisfied

- **Shore D hardness test results**



- **Shore hardness and drying time test results**

	NCO [%]	Shore hardness [D]	Drying time [sec]
Case 1	13	63	22
	15.5	66	20
	18	69	20
Case 2	13	52	40
	15.5	60	25
	18	65	10
Case 3	13	60	50
	15.5	63	46
	18	66	35

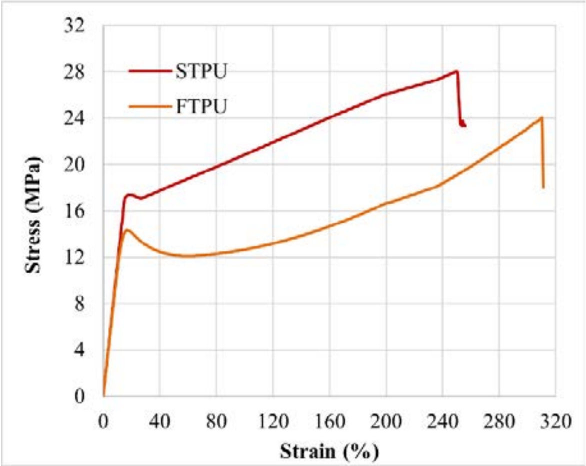
- Shore harness test: Case1 > Case3 > Case2
  18% > 15.5% > 13% (NCO(%))

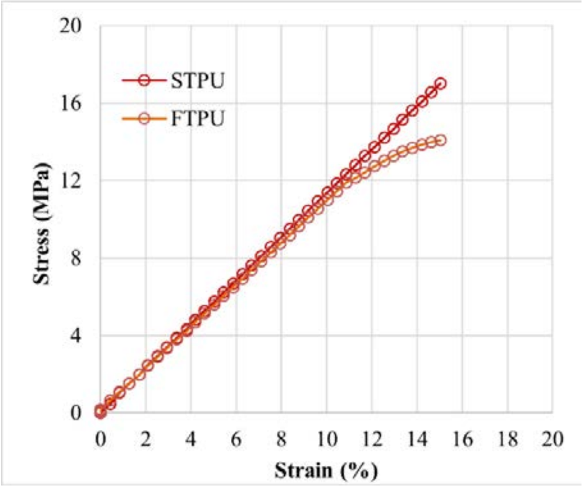
- From mechanical property test: Case 1(Monomeric MDI) with NCO 18% ➡ STPU

Comparison with Previous PU Material

Mechanical properties comparison with FTPU

- **Strain-stress comparison(Kim et al., 2010)**





- **Properties comparison between FTPU and STPU**

Properties	FTPU	STPU
Tensile strength (MPa)	24	28
Shore hardness (D)	65	69
Percent elongation (%)	310	250
Drying time (sec)	30	20

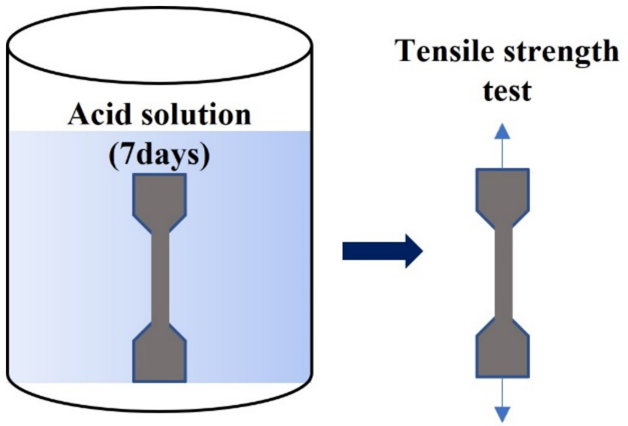
- Tensile strength: 17% improvement
- Percent elongation: 60% decrease
- Shore hardness: 6% improvement
- Drying time: 10 sec decrease

Higher strength, hardness (higher confinement effect, higher energy absorption capacity)

Durability Property Tests

Test method of durability evaluation

▪ Acid environmental exposure test



- Experiments followed KS F 4922
- Temperature of 20±2 ℃, 2% special-grade sulfuric acid solution
- 168h(1week) of immersion and then tensile strength test of 3 specimen

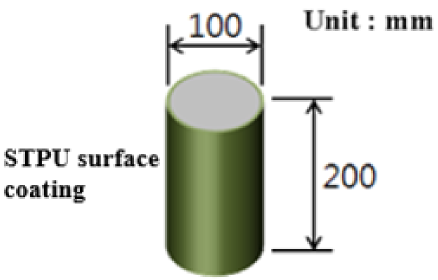
▪ UV sunlight exposure test

- Experiments followed KS F 2274
- UV light exposure for 1000h and 2000h
- The modulus was measured at 0, 100, 200, and 300 cycles

Durability Property Tests

Test method of durability evaluation

▪ Concrete carbonation resistance



- Experiments followed KS F 2584
- Temperature of 20±2 °C, relative humidity of 60% used
- CO_2 applied to the specimen was 5±0.2 %

▪ Test method of concrete freezing and thawing

- Experiments followed KS F 2456
- 1 Cycle : 4 ~ -18 ℃ → -18 ~ 4 ℃ (2 ~4 hrs)
- Elastic modulus and compressive strength was measured at 0, 300 cycles

Durability Property Test Results

Test results of durability evaluation

- **Acid environmental exposure test result**

	STPU	After exposure	Ratio
Tensile strength (MPa)	28	23	1.0:0.83
Percent elongation (%)	250	248	1.0:0.99

- **UV sunlight exposure test result**

	STPU	1,000 h	2,000 h	Ratio
Tensile Strength (MPa)	28	17	18	1.0 : 0.61 : 0.64
Percent Elongation (%)	250	175	172	1.0 : 0.70 : 0.69

Korea standard (KS F 4922)
tensile strength: 16 MPa
percent elongation: 250%(not for stiff type)

- **Concrete carbonation resistance test result**

Type	Time [weeks]	Carbonation depth [mm]	Carbonation rate modulus
Uncoated	4	16.5	8.25
Side-coated (STPU-coated)	4	11.0	5.5


uncoated


side-coated

STPU-coated concrete specimens exhibited 27.3% less carbonation dispersion

Durability Property Test Results

Test results of durability evaluation

- **Freeze-thaw test results**

Type	Cycle	Dynamic elastic modulus [Hz]	Relative dynamic elastic modulus [%]	Compressive strength [MPa]	Reduced strength [%]
Uncoated	0	23,140	74.55	39.59	11.94
	300	19,979		34.30	
Coated	0	21,977	90.88	40.11	6.16
	300	20,951		37.64	

Less effected by freeze-thaw

Less effected by freeze-thaw

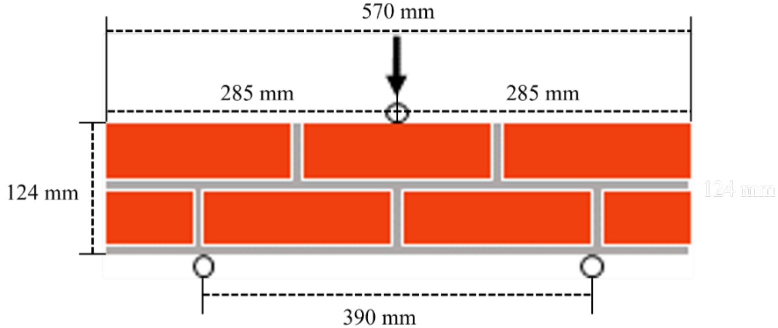
STPU has great durability for harsh environmental condition

STPU strengthening concrete specimen has better durability than non-strengthening one

STPU Retrofit Effect Evaluation -Masonry Wall-

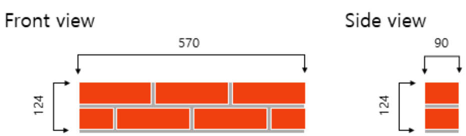
Experimental Evaluation for Masonry Wall

Flexural strength evaluation for STPU retrofitted masonry wall

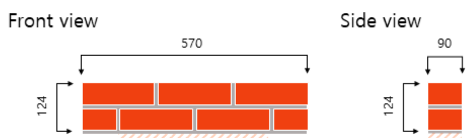


Masonry specimen details for 3 point bending test

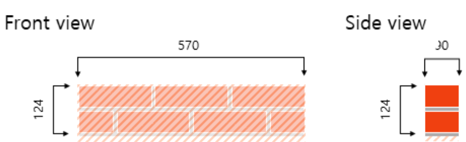
STPU application to specimen



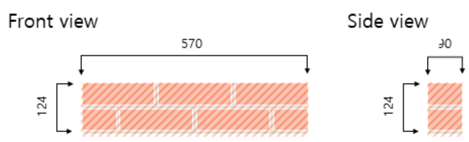
BFN



BFP



BFPS



BFPF

- 3 specimens for each different strengthening method
- STPU was applied with thickness 2 to 3 mm
- Total 12 specimens were tested

BFN

BFP

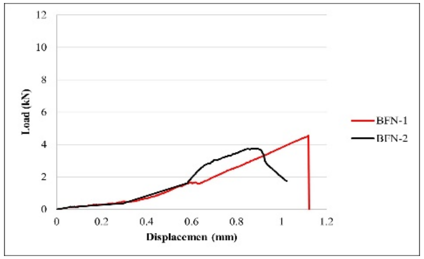
BFPS

BFPF

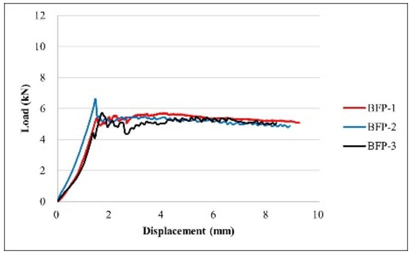
Experimental Evaluation for Masonry Wall

Flexural strength evaluation results for STPU retrofitted masonry wall

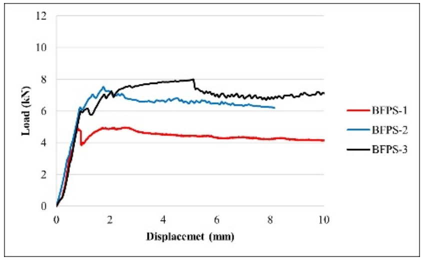
	Test Specimen number	Ultimate Load (kN)	Maximum Dis placement (mm)	Flexural Stren gth (MPa)
BFN	1	-	-	-
	2	3.75	1.02	1.59
	3	4.54	1.12	1.92
	Average	4.15	1.07	1.75
BFP	1	5.70	9.23	2.41
	2	6.94	8.87	2.93
	3	5.74	8.36	2.43
	Average	6.13	8.82	2.59
BFPS	1	4.88	12.70	2.06
	2	7.61	8.16	3.22
	3	8.24	11.74	3.48
	Average	6.91	10.87	2.92
BFPF	1	10.03	8.68	4.24
	2	6.93	9.29	2.93
	3	8.24	10.26	3.48
	Average	8.40	9.41	3.55



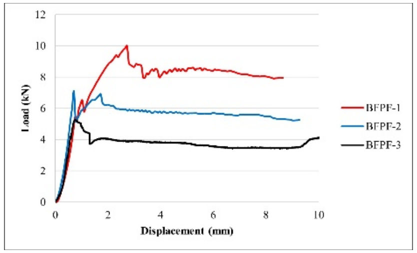
BFN



BFP



BFPS



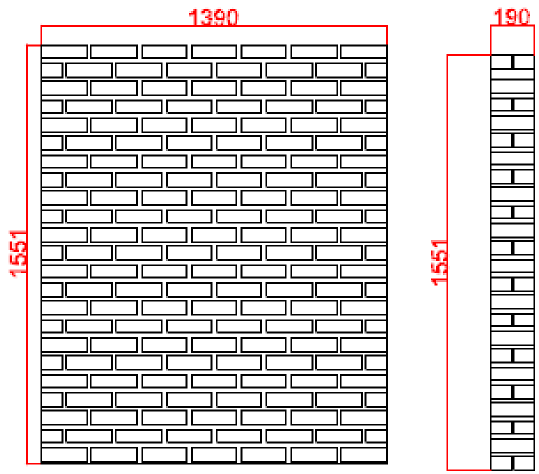
BFPF

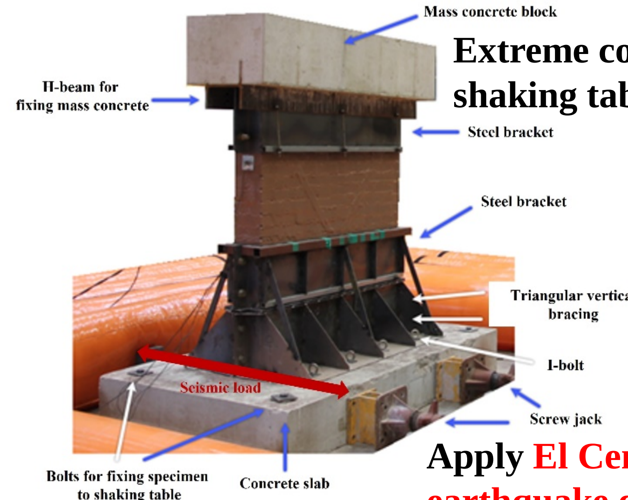
- **Flexural strength: BFPF > BFPS > BFP > BFN**
- **The difference of result exist in the same specimen**
- **Ultimate load improvement ratio compared to BFN are 48, 67, 103 % for BFP, BFPS ,BFPF respectively**
- **BFN show brittle fracture STPU strengthened specimen show ductile behavior after ultimate load**
- **Spalling of mortar occured in BFN and STPU strengthened specimens didn't**

Experimental Evaluation for Masonry Wall

Shaking table test for STPU retrofitted masonry wall

Normal shaking table test condition of masonry wall





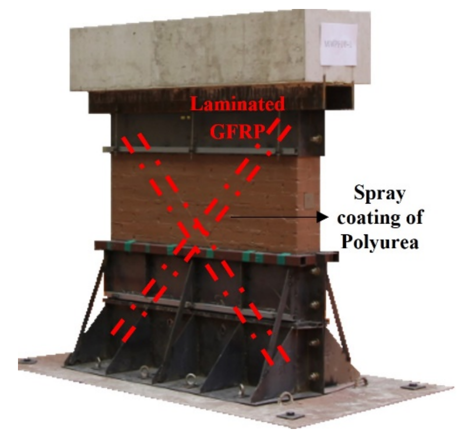
Extreme condition of shaking table test

Apply El Centro earthquake data for different PGA

LVDT, Acceleration sensors were applied

Non- strengthening
MWN type- 3 specimen

STPU 2mm strengthening
MWP2 type- 2 specimen



STPU 2mm and laminated GFRP
strengthening MWPF5 type- 2 specimen

Experimental Evaluation for Masonry Wall

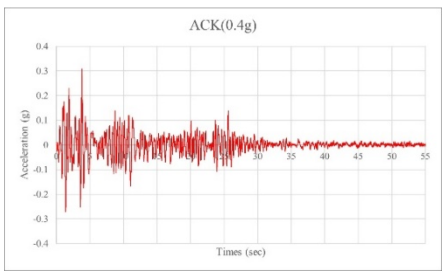
Shaking table test results for MWN(non-strengthened) specimen

Accelerometer unit: g, LVDT unit: mm

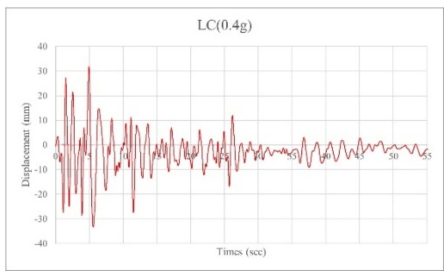
PGA. \ Spcm.	MWN-1		MWN-2		MWN-3				
	ABK	ACK	ACK	LC	ACD	ACK	LU	LC	LD
0.1 g	-0.09	-0.08	-0.08	-7.46	-0.13	-0.13	8.19	8.12	8.04
0.2 g	-0.22	0.29	-0.18	-15.77	-0.28	-0.29	-15.39	15.14	-15.24
0.3 g	-0.31	0.47	-0.26	23.89	-0.32	-0.33	24.88	24.53	24.30
0.4 g	-0.43	-0.31	0.31	-33.45	-0.57	-0.55	53.36	34.97	31.34
0.5 g	Preliminary experiment		-0.94	44.91	Failure occur				

Failure occur (MWN-3, 0.4 g)

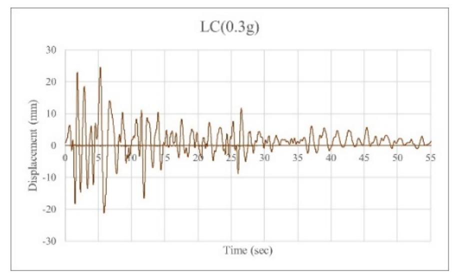
ABK: Acceleration at basement, ACK: Acceleration in center of specimen, LU: Displacement in top of specimen,
LC: Displacement in center of specimen, LD: Displacement in downward of specimen



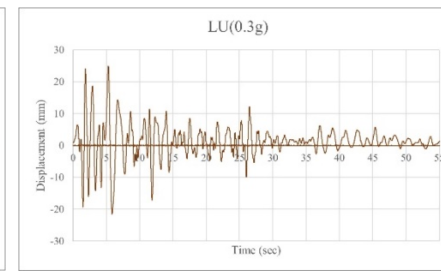
MWN-2 center acceleration(0.4g)



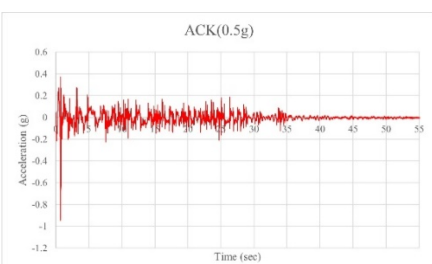
MWN-2 center displacement(0.4g)



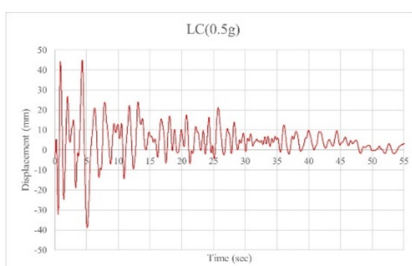
MWN-3 center displacement(0.3g)



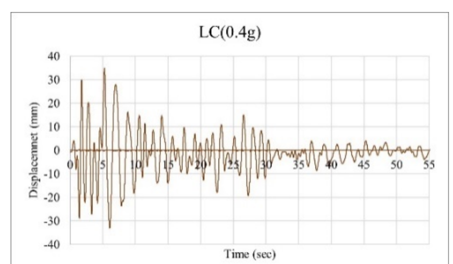
MWN-3 head displacement(0.3g)



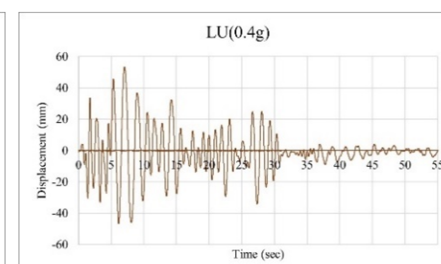
MWN-2 center acceleration(0.5g)



MWN-2 center displacement(0.5g)



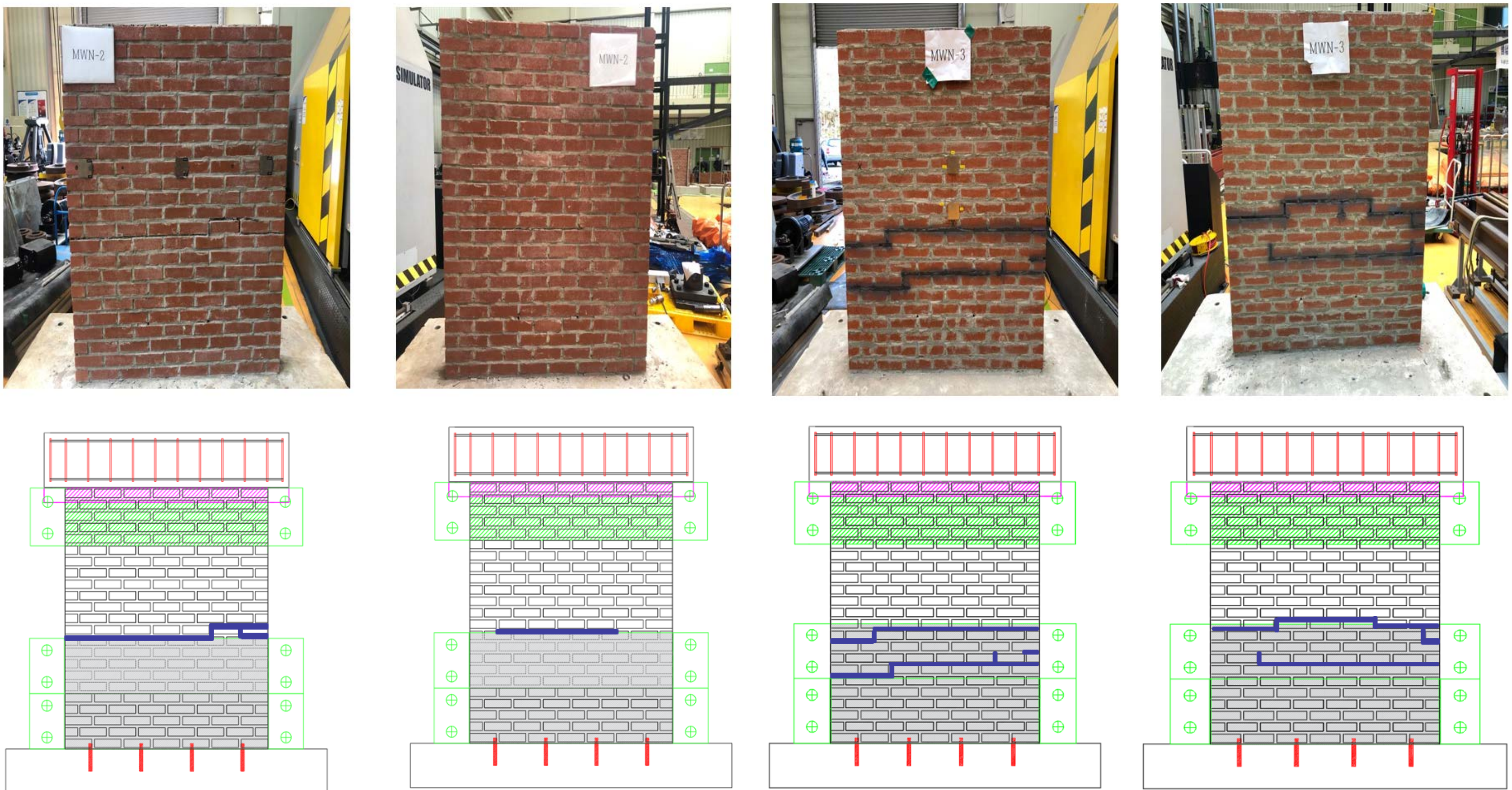
MWN-3 center displacement(0.4g)



MWN-3 head displacement(0.4g)

Experimental Evaluation for Masonry Wall

Failure mode and crack pattern of MWN specimen



front | back | front | back

MWN-2 | MWN-3

Experimental Evaluation for Masonry Wall

Shaking table test results for STPU strengthened(MWP2) specimen

Spcm. / PGA.	MWP2-1			MWP2-2			
	ABK (g)	ACK (g)	LC (mm)	ABK (g)	ACK (g)	LU (mm)	LC (mm)
0.1 g	-0.09	-0.08	-7.50	-0.08	-0.11	8.28	7.84
0.2 g	-0.22	-0.14	-15.29	-0.14	-0.2	15.48	14.97
0.3 g	-0.30	-0.18	25.25	-0.21	-0.27	25.21	24.46
0.4 g	-0.43	-0.26	32.15	-0.44	-0.51	-32.40	-31.60
0.5 g	-0.63	0.58	47.69	-0.50	0.57	-42.51	-40.02
0.6 g	-0.72	0.73	49.95	-0.65	-0.86	49.29	47.68
0.7 g	-0.81	0.88	58.78	-0.71	-1.30	59.89	57.26
0.8 g	Failure occur			-0.86	1.04	80.20	65.49

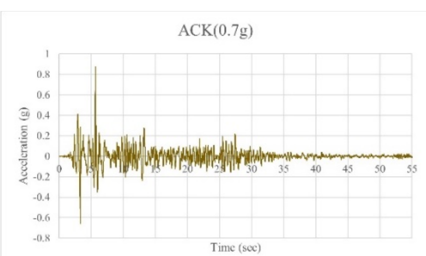
Failure occur (MWP2-2, 0.8 g)

ABK: Acceleration at basement, ACK: Acceleration in center of specimen, LU: Displacement in top of specimen, LC: Displacement in center of specimen, LD: Displacement in downward of specimen

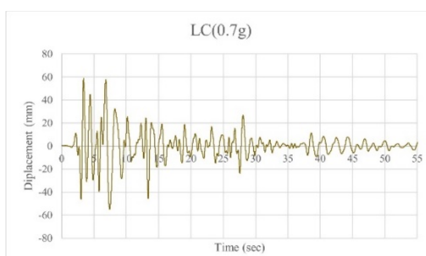
Acceleration decrease 24% compare to non-strengthened specimen

Displacement increase 0.5mm compare to non-strengthened specimen

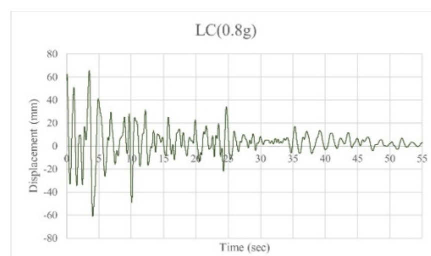
Seismic load resistance increase 0.3 g (considering PGA)



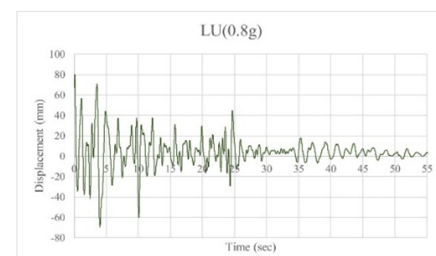
MWP2-1 center acceleration(0.7g)



MWP2-1 center displacement(0.7g)



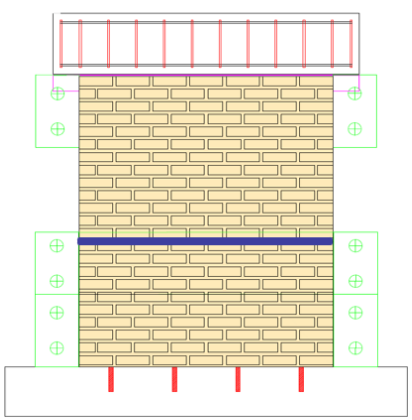
MWP2-2 center displacement(0.8g)

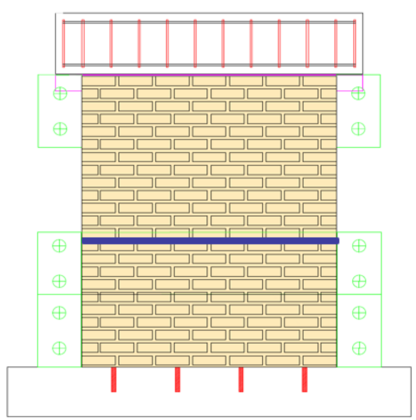


MWP2-2 head displacement(0.8g)

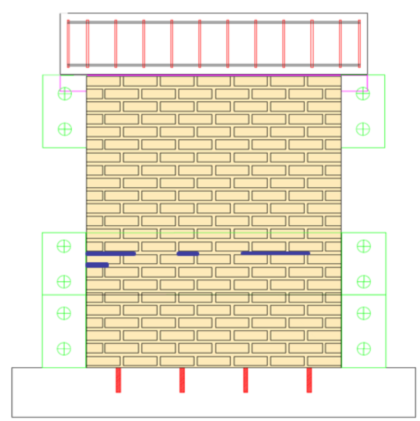
Experimental Evaluation for Masonry Wall

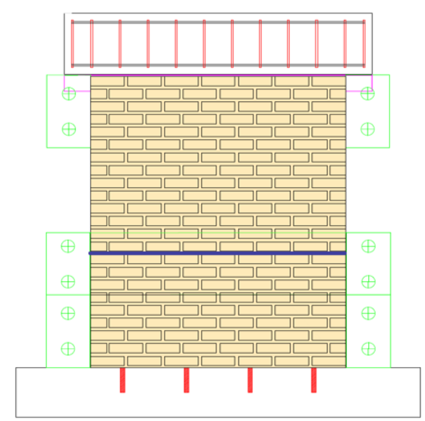
Failure mode and crack pattern of MWP2 specimen


front


back

MWP2-1


front


back

MWP2-2

Experimental Evaluation for Masonry Wall

Shaking table test results for STPU and GFRP strengthened(MWPF5) specimen

Spcm. / PGA	MWPF5-1					MWPF5-2				
	ABK (g)	ACK (g)	LU (mm)	LC (mm)	LD (mm)	ABK (g)	ACK (g)	LU (mm)	LC (mm)	LD (mm)
0.1 g	-0.14	-0.11	-7.75	7.51	7.61	-0.14	-0.13	-8.01	-7.73	-7.82
0.2 g	-0.26	-0.43	-15.85	-15.54	-15.92	-0.23	-0.29	-16.18	-19.44	-15.76
0.3 g	-0.32	-0.41	24.17	24.05	23.76	-0.34	-0.31	26.24	25.50	25.68
0.4 g	-0.43	-0.61	-32.84	-32.52	-31.72	-0.43	-0.54	-34.74	-34.27	-33.68
0.5 g	-0.52	-0.63	-41.93	40.81	39.68	-0.57	-0.71	47.94	43.41	45.16
0.6g	-0.68	-1.04	51.65	48.62	46.96	-0.75	-1.22	-52.83	-48.68	-49.80
0.7g	-0.76	-0.81	63.48	56.47	54.00	-0.80	1.00	63.66	59.42	60.68
0.8g	-0.84	-1.18	83.85	72.39	67.83	-0.92	1.11	74.07	64.63	67.04
0.9g	-1.00	-1.82	-103.53	85.37	-79.03	-1.05	-1.15	-106.68	-90.43	-100.67
1.0g	-1.01	1.80	-133.04	84.97	-94.48	-	-	-	-	-

Failure occur (MWPF5-1, 1.0g)

Failure occur (MWPF5-2, 0.9g)

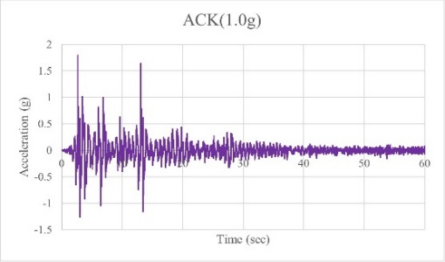
ABK: Acceleration at basement, ACK: Acceleration in center of specimen, LU: Displacement in top of specimen, LC: Displacement in center of specimen, LD: Displacement in downward of specimen

Acceleration increase 32 % compare to non-strengthened specimen

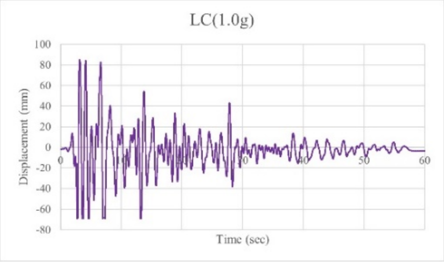
Displacement increase 2.5% compare to non-strengthened specimen

Seismic load resistance increase 0.5 g (considering PGA)

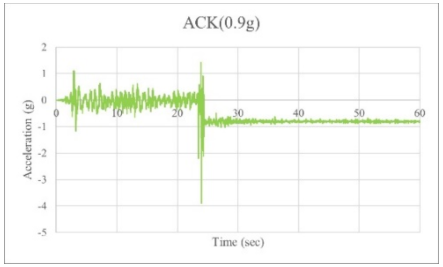
GFRP has a more dominant reinforcing effect than STPU



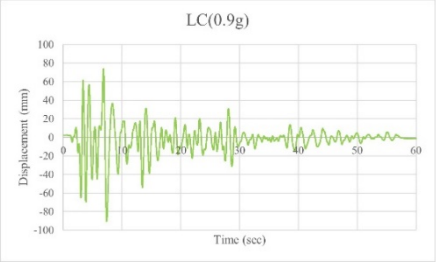
MWPF5-1 center acceleration(1.0g)



MWPF5-1 center displacement(1.0g)



MWPF5-2 center displacement(0.9g)



MWPF5-2 head displacement(0.9g)

Experimental Evaluation for Masonry Wall

Failure mode and crack pattern of MWPF5 specimen

front back front back

MWPF5-1 MWPF5-2

Relative displacement results

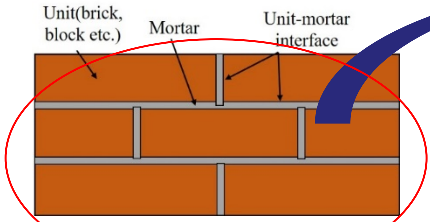
PGA. \ Spcm.	MWN-3		MWP2-2		MWPF5-1		MWPF5-2	
	LU (mm)	LC (mm)	LU (mm)	LC (mm)	LU (mm)	LC (mm)	LU (mm)	LC (mm)
0.1 g	0.37	0.20	0.26	0.19	-0.81	-0.40	-0.27	0.19
0.2 g	-1.06	0.31	-0.57	-0.28	-1.05	0.88	0.63	0.49
0.3 g	-1.92	0.51	-0.75	0.32	-2.45	-1.15	-1.77	1.21
0.4 g	40.72 (Failure)	14.14 (Failure)	-1.50	0.58	-4.06	-1.80	-3.38	2.40
0.5 g	-	-	-3.06	1.26	-5.26	-2.21	-4.12	2.26
0.6g	-	-	-3.16	1.30	-10.64	-4.37	-4.36	-5.02
0.7g	-	-	-3.88	-1.67	-12.61	-5.31	-4.70	-5.36
0.8g	-	-	13.80 (Failure)	-6.43 (Failure)	27.01	-8.83	7.28	-8.64
0.9g	-	-	-	-	51.16	17.77	-53.21 (Failure)	-29.12 (Failure)
1.0g	-	-	-	-	67.08 (Failure)	30.53 (Failure)	-	-

LU: Displacement in top of specimen, LC: Displacement in center of specimen

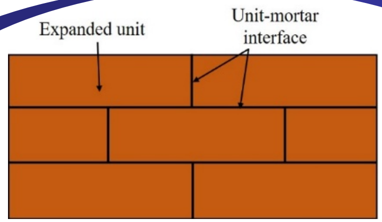
- **For the inherent displacement of the specimen due to seismic load, the relative displacement is needed**
- **Relative displacement : Masonry wall displacement – shaking table displacement**
- **Relative displacement is high in order of MWN, MWPF5, MWP2**
- **The MWP2 and MWPF5 specimens show safe behavior at 0.4g (IBC seismic resistance standard for masonry wall)**

Numerical Evaluation for Masonry Wall

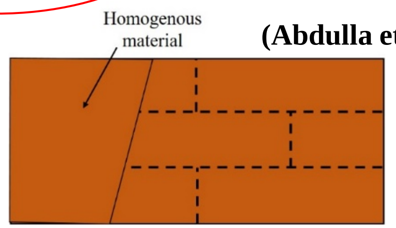
Masonry wall modeling details for flexural strength test (ABAQUS)



Detailed micro-model

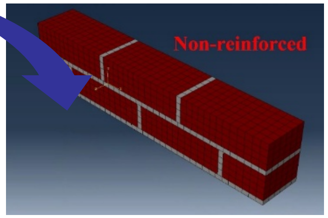


Simplified micro-model

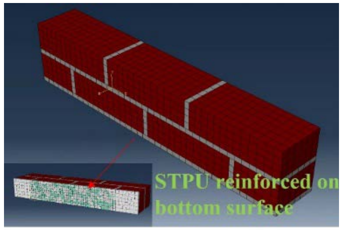


Macro-model

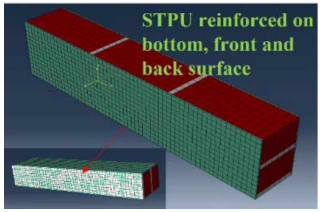
(Abdulla et al. 2017)



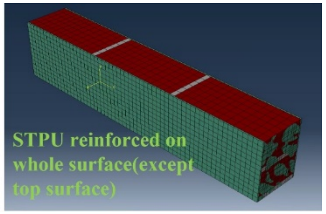
BFN



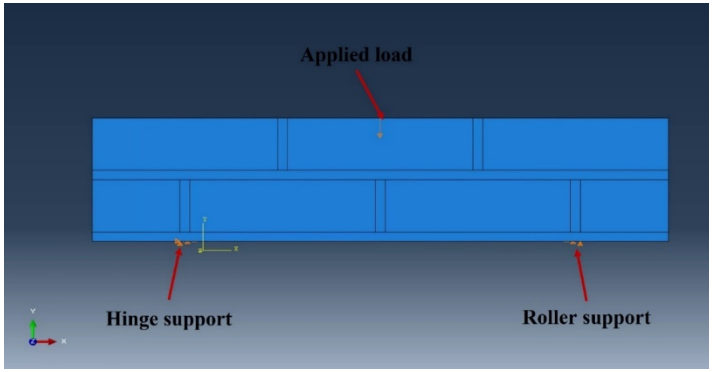
BFP



BFPS



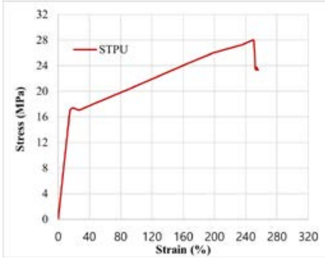
BFPF



Boundary condition

CDP (Concrete damaged plasticity) model properties (Bhosale and Desai, 2019; Borah et al., 2020)

	Density (kg/m^3)	Elastic Modulus (MPa)	ν	ψ	ϵ	σ_{b0}/σ_{c0}	K_c	μ
Brick	2100	5730	0.15	28	0.1	1.16	0.667	0
Mortar	2400	14000	0.2	40	0.1	1.16	0.667	0

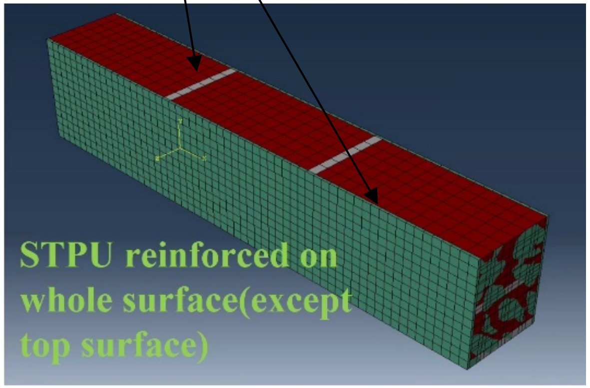


Real test data of STPU → Arruda-Boyce model

Numerical Evaluation for Masonry Wall

Properties of joint interfaces in flexural strength test

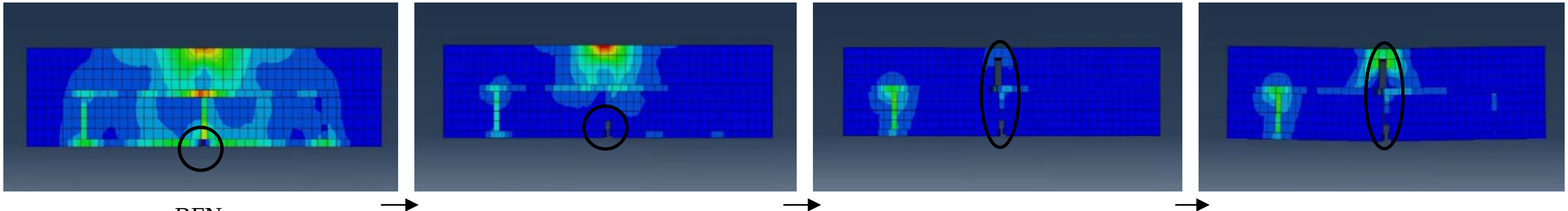
	Tangential behavior	Cohesive behavior			
	Friction coefficient	Stiffness of joint in the normal direction K_{nn} (N/mm²)	Stiffness of joint in the first shear direction K_{ss} (N/mm²)	Stiffness of joint in the second shear direction K_{tt} (N/mm²)	
Brick-Mortar	0.75	35	14.42	14.42	(Li and Zeng, 2023)
Brick-STPU	0.06	4160	1750	1750	(Gattesco et al., 2015)



Numerical Evaluation for Masonry Wall

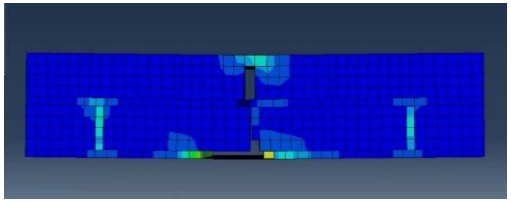
Numerical analysis result of flexural strength test

- **Element spalling and crack pattern**

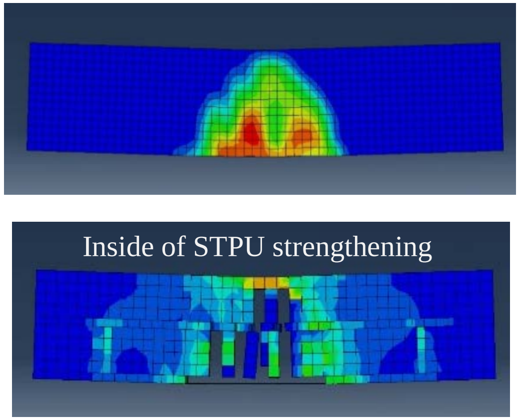


BFN

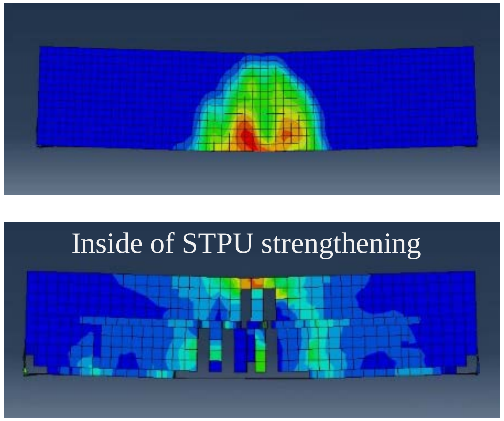
Crack pattern and progression(bottom middle to top) are well described



BFP



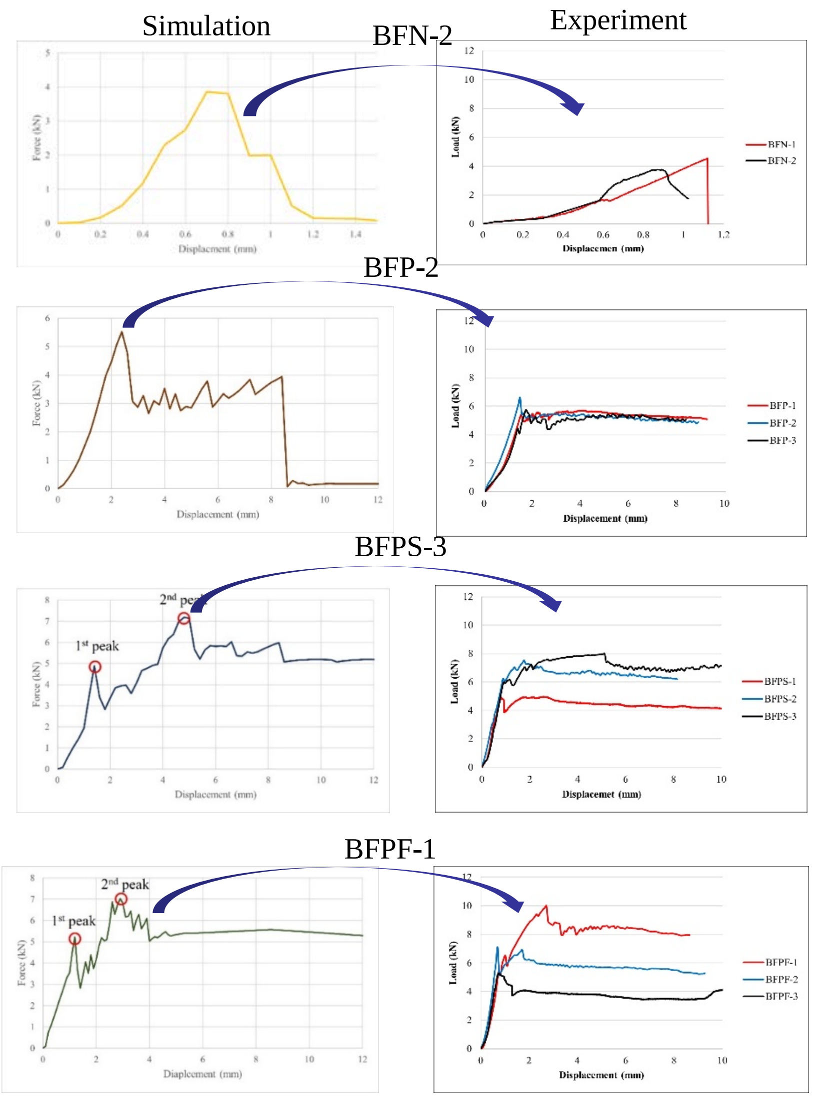
BFPS



BFPF

Numerical Evaluation for Masonry Wall

Comparison between numerical and experimental result

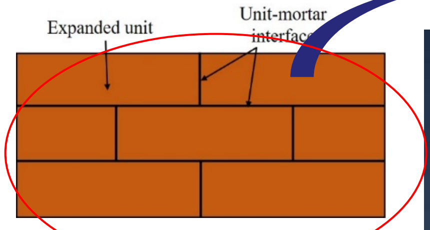


Specimen	Data type	Ultimate Load (kN)	Maximum Dis placement (mm)	Flexural Stren gth (MPa)
BFN	Numerical	3.86	0.80	1.63
	Experimental	4.15	1.07	1.75
	Ratio	0.93	0.75	0.93
BFP	Numerical	5.52	8.40	2.34
	Experimental	6.13	8.82	2.59
	Ratio	0.90	0.95	0.90
BFPS	Numerical	7.18	-	3.04
	Experimental	6.91	10.87	2.92
	Ratio	1.04	-	1.04
BFPF	Numerical	7.03	-	2.97
	Experimental	8.40	9.41	3.55
	Ratio	0.84	-	0.84

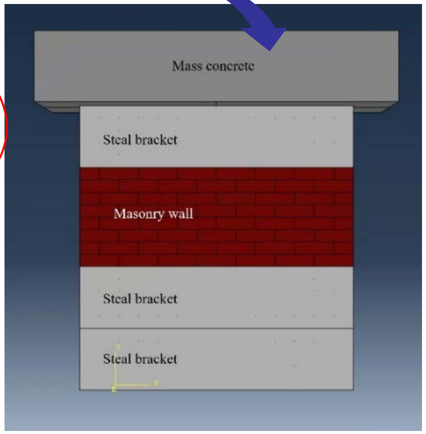
- **Analysis of the ultimate load revealed that BFPF was off by 16%, whereas the other specimens were off by less than 10%. For BFN and BFP**
- **The maximum displacement error was 25% (0.27mm), and for BFP, it was 5%**
- **The load-displacement curves are similarly described in numerical analysis**
- **The masonry wall numerical model is reliable (considering non-linearity)**

Numerical Evaluation for Masonry Wall

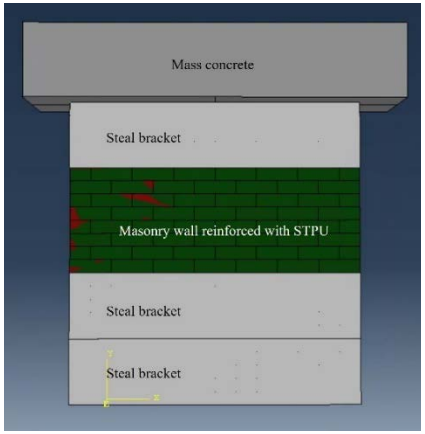
Masonry wall modeling for shaking table test (ABAQUS)



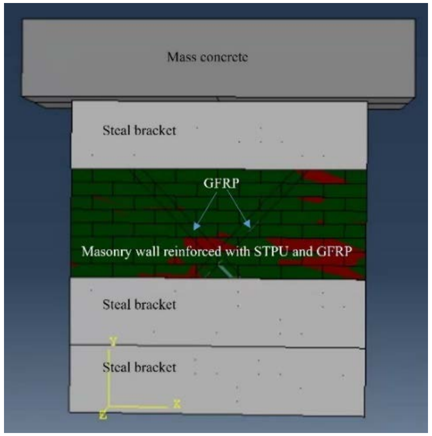
Simplified micro-model
(Abdulla et al., 2017)



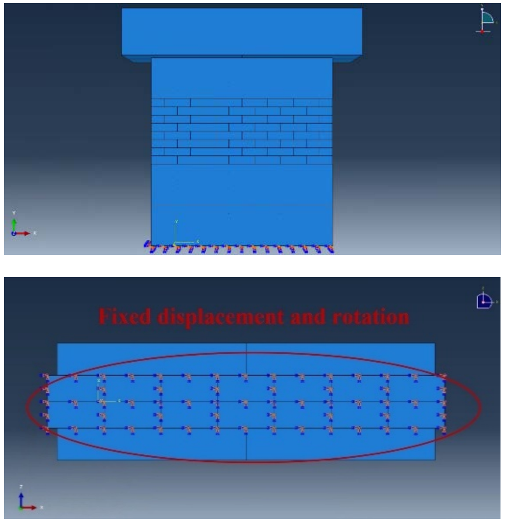
MWN



MWP2



MWPF5



Boundary condition

Drucker-Prager material properties (Abdulla et al., 2017)

	Density (kg/m^3)	Elastic Modulus (MPa)	ν	ψ	Flow stress ratio	Angle of friction	Yield compressive stress (MPa)
Expanded unit	1800	2,888	0.15	11.3	1	36	16

STPU → Arruda-Boyce model

Laminated GFRP → Elastic-lamina type

Acceleration data from the real test → Seismic load

Numerical Evaluation for Masonry Wall

GFRP properties and joint interfaces properties in shaking table test

▪ GFRP material properties (Gattesco et al., 2015)

GFRP elastic property	Value
Density (kg/m^3)	1,900
Longitudinal modulus, E_1 (GPa)	73
Transverse modulus, E_2 (GPa)	18
In-plane Poisson's ratio, ν_{12}	0.25
In-plane shear modulus, G_{12} (GPa)	9
Transverse shear modulus, G_{13} (GPa)	9
Through-thickness shear modulus, G_{23} (GPa)	7

▪ GFRP fail stress (Gattesco et al., 2015)

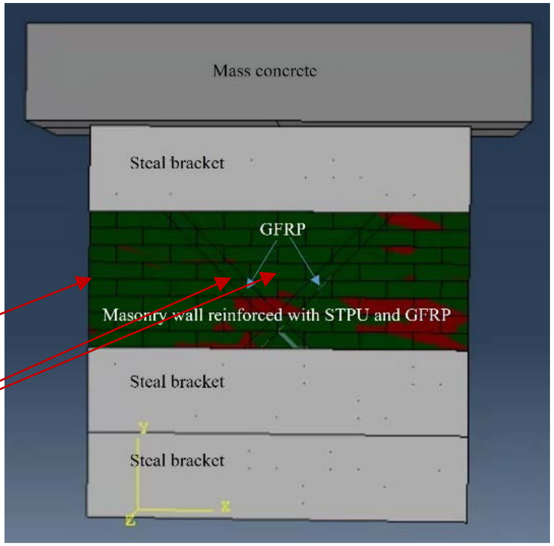
Fail stress property	Fail stress
Tensile stress in fiber direction (MPa)	1,500
Compressive stress in fiber direction (MPa)	-700
Tensile stress in transverse direction (MPa)	90
Compressive stress in transverse direction (MPa)	-140
Shear strength (MPa)	6

▪ Joint interfaces properties

	Tangential behavior	Cohesive behavior		
	Friction coefficient	Stiffness of joint in the normal direction K_{nn} (N/mm^2)	Stiffness of joint in the first shear direction K_{ss} (N/mm^2)	Stiffness of joint in the second shear direction K_{tt} (N/mm^2)
Brick-Brick	0.75	63	25	25
Brick-STPU, Brick-GFRP	0.06	4,160	1,750	1,750

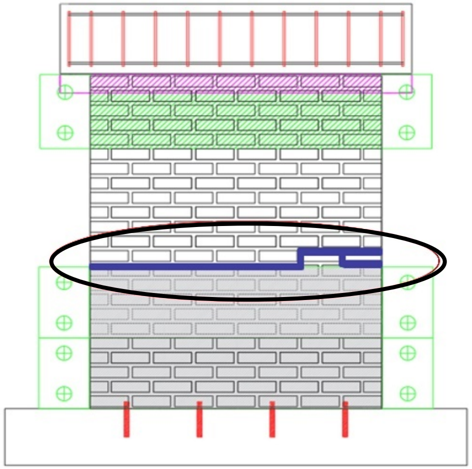
(Abdulla et al, 2017)

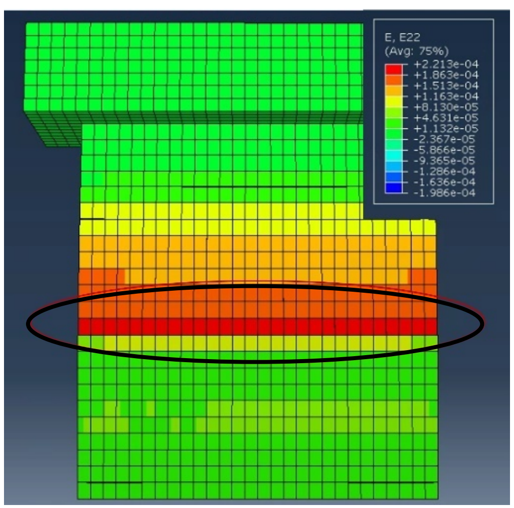
(Gattesco et al., 2015)



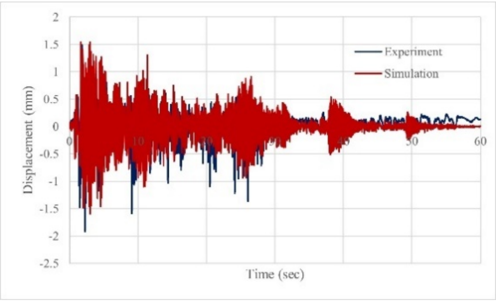
Numerical analysis result of shaking table test

- **Comparison of failure mode patterns**

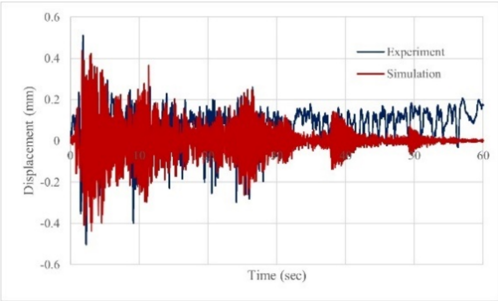




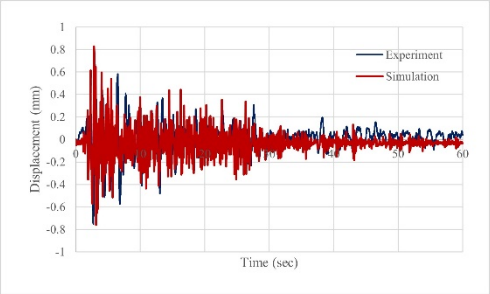
- **Comparison of time-displacement graph**



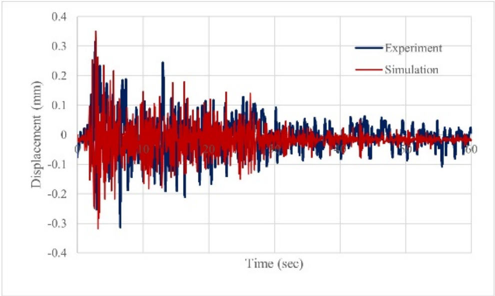
MWN LU (0.3g)



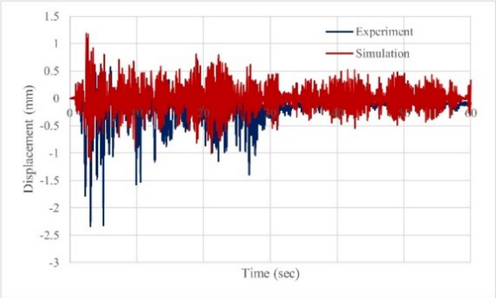
MWN LC (0.3g)



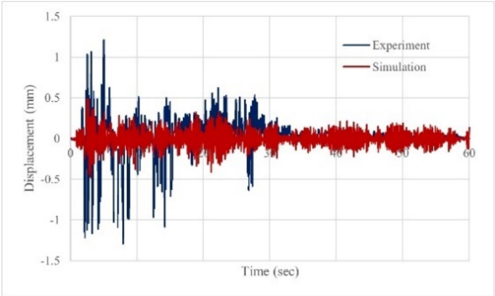
MWP2 LU (0.3g)



MWP2 LC (0.3g)



MWPF5 LU (0.3g)



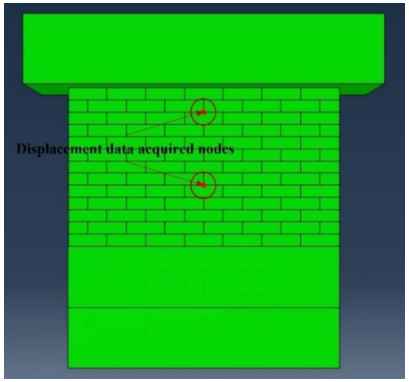
MWPF5 LC (0.3g)

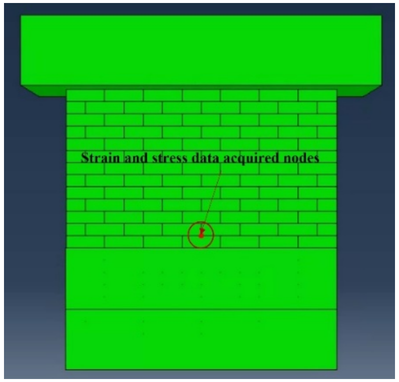
Numerical Evaluation for Masonry Wall

Numerical analysis result of shaking table test

PGA. \ Spcm.		MWN				MWP2				MWPF5			
		LU (mm)	LC (mm)	Strain	Stress (MPa)	LU (mm)	LC (mm)	Strain	Stress (MPa)	LU (mm)	LC (mm)	Strain	Stress (MPa)
0.1 g	Max.	0.62	0.17	0.00008	0.22	0.32	0.13	0.00006	0.15	0.53	0.21	0.00008	0.20
	Min.	-0.60	-0.16	-0.00007	-0.20	-0.31	-0.13	-0.00007	-0.20	-0.46	-0.20	-0.00010	-0.25
0.2 g	Max.	0.84	0.23	0.00012	0.32	0.77	0.31	0.00008	0.21	0.75	0.32	0.00011	0.28
	Min.	-0.84	-0.23	-0.00001	-0.27	-0.52	-0.22	-0.00014	-0.36	-0.71	-0.29	-0.00012	-0.30
0.3 g	Max.	1.55	0.44	0.00019	0.52	0.83	0.35	0.00011	0.28	1.19	0.49	0.00017	0.45
	Min.	-1.60	-0.44	-0.00019	-0.51	-0.76	-0.32	-0.00011	-0.29	-1.15	-0.48	-0.00015	-0.37
0.4 g	Max.	2.18	0.90	0.00024	0.66	1.48	0.62	0.00009	0.25	1.56	0.66	0.00012	0.31
	Min.	-1.98	-0.83	-0.0027	-0.75	-0.70	-0.30	-0.00017	-0.49	-0.98	-0.42	-0.0002	-0.51
0.5 g	Max.	-	-	-	-	1.36	0.57	0.00014	0.40	2.37	0.98	0.00022	0.30
	Min.	-	-	-	-	-1.15	-0.49	-0.00020	-0.55	-1.61	-0.67	-0.00031	-0.23
0.6 g	Max.	-	-	-	-	2.01	0.83	0.00016	0.43	2.07	0.85	0.00021	0.56
	Min.	-	-	-	-	-1.12	-0.46	-0.00028	-0.76	-1.40	-0.58	-0.00026	-0.64
0.7 g	Max.	-	-	-	-	2.44	1.02	0.00015	0.41	2.05	0.85	0.00027	0.68
	Min.	-	-	-	-	-1.27	-0.53	-0.00032	-0.88	-1.93	-0.81	-0.00026	-0.67
0.8 g	Max.	-	-	-	-	2.72	1.15	0.00015	0.41	2.70	1.14	0.00030	0.76
	Min.	-	-	-	-	-1.36	-0.57	-0.00032	-0.90	-2.21	-0.93	-0.00034	-0.88
0.9 g	Max.	-	-	-	-	-	-	-	-	3.16	1.34	0.00039	0.99
	Min.	-	-	-	-	-	-	-	-	-3.00	-1.25	-0.00041	-1.05

: Failure occurrence : Crack occurrence





- **Based on the study of Yang et al. (2019), cracking was considered to occur when the strain exceeded 0.00015**
- **Based on the mortar tensile strength, the specimen was considered destroyed when the stress exceeded 0.8 MPa.**
- **The strain and displacement at the same load are high in the order MWN > MWPF5 > MWP2**
- **The stress in the central parts of specimens MWN, MWP2, and MWPF5 exceeds 0.8 MPa when the PGA values are 0.5g, 0.7g, and 0.8g, respectively**
- **The PGA of the specimen's destruction occur in numerical analysis is similar to those in the shaking table test**

Numerical Evaluation for Masonry Wall

Comparison between numerical and experimental result

PGA \ Specimen		MWN LU (mm)	MWN LC (mm)	MWP2 LU (mm)	MWP2 LC (mm)	MWPF5 LU (mm)	MWPF5 LC (mm)
0.1 g	Experiment	0.37	0.20	0.26	0.19	0.27	0.19
	Simulation	0.62	0.17	0.32	0.13	0.53	0.21
0.2 g	Experiment	1.06	0.31	0.57	0.28	0.63	0.49
	Simulation	0.84	0.23	0.77	0.31	0.75	0.32
0.3 g	Experiment	1.92	0.51	0.75	0.32	1.77	1.21
	Simulation	1.60	0.44	0.83	0.35	1.19	0.49
0.4 g	Experiment	40.72 (failure)	14.14 (failure)	1.50	0.58	3.38	2.40
	Simulation	2.78	0.88	1.48	0.62	1.56	0.66
0.5 g	Experiment	-	-	3.06	1.26	4.12	2.26
	Simulation	-	-	1.36	0.57	2.37	0.98
0.6 g	Experiment	-	-	3.16	1.3	4.36	5.02
	Simulation	-	-	2.01	0.83	2.07	0.85
0.7 g	Experiment	-	-	3.88	1.67	4.70	5.36
	Simulation	-	-	2.44	1.02	2.05	0.85
0.8 g	Experiment	-	-	13.8 (failure)	6.43 (failure)	7.28	8.64
	Simulation	-	-	2.72	1.15	2.70	1.14
0.9 g	Experiment	-	-	-	-	53.21 (failure)	29.12 (failure)
	Simulation	-	-	-	-	3.16	1.34

- The MWN specimens have considerably similar results with errors of less than 0.32 mm for both LU and LC when the PGA is 0.1g–0.3g

- The results of specimens MWP2 and MWPF5 are considerably similar with a maximum difference of 0.58 mm when the PGA is 0.1g–0.3g

- When the PGA exceeds 0.3g, errors of up to 1.7 and 4.58 mm for the LU values of MWP2 and MWPF5 are observed

- These errors occur because uniform test results are difficult to derive due to the material characteristics of the masonry wall

- The deviation of test result is considerable, and the cracks and destruction that occur during the experiment are not depicted by the method used in the numerical analysis

- The masonry wall numerical model is well described the masonry wall behavior

Numerical Evaluation for Masonry Wall

Parametric study for thickness of STPU

Thickness		Numerical analysis result			
		LU (mm)	LC (mm)	Strain	Stress (MPa)
1 mm	Max.	1.54	0.65	0.000095	0.26
	Min.	-0.80	-0.33	-0.000187	-0.53
2 mm	Max.	1.48	0.62	0.000093	0.25
	Min.	-0.70	-0.30	-0.0000174	-0.49
3 mm	Max.	1.50	0.61	0.000118	0.31
	Min.	-0.81	-0.37	-0.000189	-0.51
4 mm	Max.	1.51	0.66	0.000119	0.32
	Min.	-0.82	-0.34	-0.000196	-0.54
5 mm	Max.	1.51	0.64	0.000114	0.31
	Min.	-0.79	-0.33	-0.000175	-0.50
6 mm	Max.	1.51	0.64	0.000103	0.28
	Min.	-0.79	-0.33	-0.00016	-0.46
7 mm	Max.	1.51	0.64	0.000116	0.32
	Min.	-0.79	-0.33	-0.000187	-0.51
8 mm	Max.	1.54	0.66	0.000111	0.32
	Min.	-0.80	-0.34	-0.000192	-0.52

- **The parametric study was conducted using thickness as a variable (same seismic load PGA 0.4g)**
- **The most effective strengthening thickness is 2 mm**
- **The strengthening effect is getting weaker after the thickness exceed 6 mm**
- **It is the similar results from Park et al. (2011) study that strengthening effect is getting weaker after the polyurea's thickness exceed 6 mm**

Conclusions

Conclusions

Stiff-type polyurea material development

- The material development was conducted to enhance strengthening effect of existing polyurea material. Improving stiffness and tensile strength of polyurea, the stiff-type polyurea(STPU) is developed. And STPU shows great durability

STPU strengthening effect evaluation for masonry wall

- From flexural strength test, the more STPU is applied to the masonry wall surface, the higher flexural strength and ductile behavior are observed. From shaking table test, STPU strengthen specimen shows great seismic load resistance and ductile behavior. And numerical analysis model for STPU strengthened masonry wall was constructed. The model shows similar results as experimental results.

Further study

- Parametric study of masonry wall numerical model for various interface condition and STPU thickness

Thank you for your attention