

2018 KEPIC-Week (제16회)
Advanced Standards & Global Partner
부산 해운대 그랜드 호텔

SC벽체 충돌하중 저항성능 평가



2018. 08. 28.

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□ 연구 배경 및 목표

○ 충돌하중에 대한 구조설계

- 항공기 충돌, 미사일 공격, 비산물 충돌 등은 국가 중요 시설물들에 구조설계에 중요하게 다루어짐.
- 북한의 미사일 발사 등 사회기반시설물의 항공기 충돌 안전성에 대한 사회적 관심 증대
- SC구조 국부손상평가 → 국내의 경우 설계기준 부재, 국외의 경우 AISC N690s1-15 (2015)

○ 연구현황

- RC구조와 비교하여 강판콘크리트(SC)구조의 충돌하중에 대한 국부손상평가 연구는 상대적으로 부족함.
 - AISC의 SC구조 평가식의 경우에도 SC구조의 거동을 적절히 반영하지 못함.
 - SC구조의 충돌하중에 대한 성능이 일부 연구에서 입증됨.
- 실규모 실험의 비용, 장비 기술, 환경 등의 한계 → 수치해석을 통하여 많은 연구가 수행됨.
- 기존 연구에서의 SC구조 수치해석모델들은 이론 및 실험적 근거가 부족함.
 - 대부분의 연구에서 erosion parameter는 실험결과에 의해 보정된 값으로 정의됨
 - 순수 SC벽체에 대한 실험적 검증이 미비함. (기존 연구는 RC+Steel plate)

본 연구는 다수의 중규모 실험결과를 기반으로 SC구조의 충돌하중에 대한 국부 손상 평가식을 제안한다.

2. 중규모 충돌실험

■ 실험계획

- ✓ 총 15개 실험체 : 13 SC + 2 RC (예비실험체 1개 포함)
- ✓ 변수 : 벽체두께, 강판비, 강재 항복강도, 타이바 유무
- ✓ 각 실험체 당 관통속도를 달리하여 2회 실험 수행

No	ID	T	tp	2tp/T	fy	fc'	(2tp/T)x (fy/f'c)	Tie bar	W	관통속도 (평가식)	Expected Behavior	개수	스터드 (mm)			타이바 (mm)	
		(mm)	(mm)	%	(MPa)	(MPa)	(Varma)	(kg)	(m/s)	(per Varm a Eq.)	지름		몬힘 깊이	중간 격	지름	간격	
1	SC-T320-3.7	320	6	3.75%	355	35	38%	X	60	122	Perforated/ Stopped	2	9	72	180		
2	SC-T320-3.7-tie	320	6	3.75%	355	35	38%	○	60	122+	Perforated/ Stopped	2	9	72	180	10	180
3	SC-T480-3.7	480	9	3.75%	355	35	38%	x	80	160	Perforated/ Stopped	2	9	72	180		
4	SC-T240-5.0	240	6	5.00%	355	35	50%	x	40	130	Perforated/ Stopped	2	9	72	180		
5	SC-T360-5.0	360	9	5.00%	355	35	50%	x	60	159	Perforated/ Stopped	2	9	72	180		
6	SC-T360-5.0-tie	360	9	5.00%	355	35	50%	○	60	159+	Perforated	1	9	72	180	10	
7	SC-T360-5.0-s	360	9	5.00%	460	35	66%	x	80	147	Perforated/ Stopped	2	9	72	180		
8	RC-T320-3.7	320	Rebar	3.75%	-	35	-	x	60	113/78	Perforated/ Stopped	2					
											Total	15					

2. 중규모 충돌실험

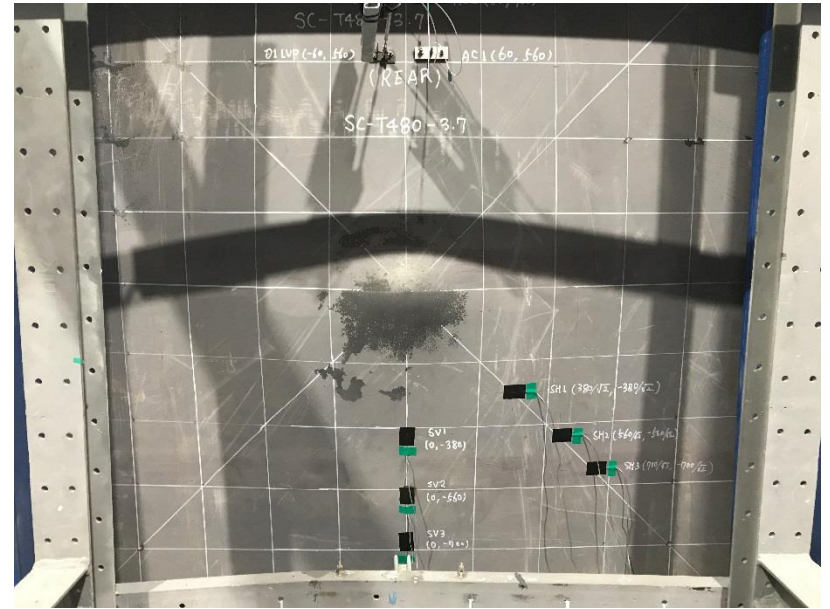
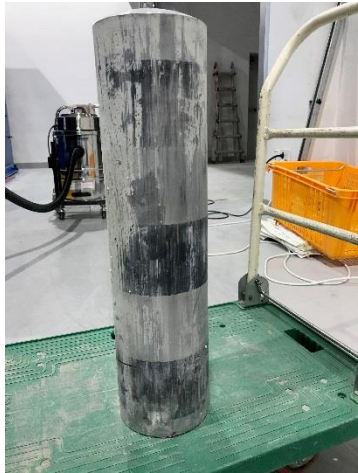
실험체 #3 SC-T480-3.7 Test 1



발사속도	해석 관통속도	설계식 관통속도	결과
197 m/s	195/200/210 m/s	160 m/s	미관통

전면

후면



2. 중규모 충돌실험

Summary of Test Result

Test summary									Test results		
No	Specimen ID	Test	f'c		W		V		Impact test summary		
			Nominal	Test	Target	Test	Target	Test	Perforated /Stopped	Residual deflection (mm)	Residual velocity (m/s)
			(MPa)	(MPa)	(kg)	(kg)	(m/s)	(m/s)			
1	SC-T320-3.7-SM	1	35	31.8	60	60.90	165	165.3	Stopped	176	-
		2		34.8		-	-	-	-	-	-
2	SC-T320-3.7-tie-SM	1		34.2	60	60.95	165	165.2	Stopped	164	-
		2		32.6		60.90	180	180	Perforated	-	58.8
3	SC-T480-3.7-SM	1		37.5	80	81.90	200	197.5	Stopped	186	-
		2		35.4		81.70	230	224.2	Perforated	-	-
4	SC-T240-5.0-SM	1		34.5	40	40.20	190	203	Perforated	-	-
		2		29.7		40.18	170	178.5	Stopped	175	-
5	SC-T360-5.0-SM	1		37.1	60	60.75	180	180	Stopped	131	-
		2		31.2		60.80	200	198.5	Stopped	170	-
6	SC-T360-5.0-tie-SM	1		33.5	60	60.75	180	179.3	Stopped	114	-
		2		-		-	-	-	-	-	
7	SC-T360-5.0-HSA	1		32.9	80	78.80	160	167.6	Perforated	-	45.5
		2		32.5		78.70	130	-	Stopped	73	-
8	RC-T320-3.7	1		30.8	60	60.95	140	142.6	Perforated	-	-
		2		36.2		60.90	100	105	Stopped	-	-

+Displacement, Strain and Acceleration gauges

3. 소규모 실험결과

- Specimen identifier : $\rho(\%)$ - $\rho_t(\%)$ - f_y -D- W_t - V_o
- Gr.1 → Gr.2 (different ρ) → Gr.3 (different f_y)

**AISC
N690**

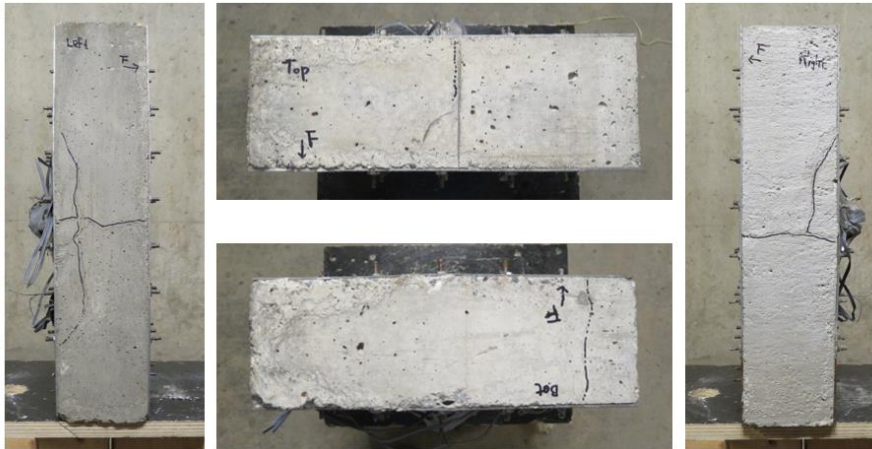


Test group	Specimen identifier	SC wall					Projectile			Expected result	
		ρ (%)	S/t_{sc}	ρ_t (%)	f'_c (ksi)	f_y (ksi)	Dia. (in)	W_t (lb)	V_o (ft/s)		
	1	3-0.37-50-1.0-1.3-554	3.7	0.5	0.37	5	50	1.0	1.3	554	Stopped
	2	3-0.37-50-1.0-1.3-677	3.7	0.5	0.37	5	50	1.0	1.3	677	Perforated
	3	3-0.37-50-1.0-2.0-430	3.7	0.5	0.37	5	50	1.0	2.0	430	Stopped
	4	3-0.37-50-1.0-2.0-525	3.7	0.5	0.37	5	50	1.0	2.0	525	Perforated
Gr. 1	5	3-0.53-50-1.5-1.3-660	3.7	0.5	0.53	5	50	1.5	1.3	660	Stopped
1	6	3-0.53-50-1.5-1.3-750	3.7	0.5	0.53	5	50	1.5	1.3	750	Perforated
	7	3-0.53-50-1.0-2.0-513	3.7	0.5	0.53	5	50	1.0	2.0	513	Stopped
	8	3-0.53-50-1.0-2.0-626	3.7	0.5	0.53	5	50	1.0	2.0	626	Perforated
	9	3-1.23-50-1.5-3.5-380	3.7	0.5	1.23	5	50	1.5	3.5	380	Stopped
	10	3-1.23-50-1.5-3.5-465	3.7	0.5	1.23	5	50	1.5	3.5	465	Perforated
	1	5-0.48-50-1.0-2.0-445	5.2	1.0	0.48	5	50	1.0	2.0	445	Stopped
Gr. 2	2	5-0.48-50-1.0-2.0-544	5.2	1.0	0.48	5	50	1.0	2.0	544	Perforated
2	3	5-0.48-50-1.5-3.5-408	5.2	1.0	0.48	5	50	1.5	3.5	408	Stopped
	4	5-0.48-50-1.5-3.5-498	5.2	1.0	0.48	5	50	1.5	3.5	498	Perforated
Gr. 3	1	3-0.37-65-1.0-2.0-443	3.7	0.5	0.37	5	65	1.0	2.0	443	Stopped
3	2	3-0.37-65-1.0-2.0-541	3.7	0.5	0.37	5	65	1.0	2.0	541	Perforated

**** Planned with 90%~110% of AISC velocity → Changed to 130+%**

3. 소규모 실험결과

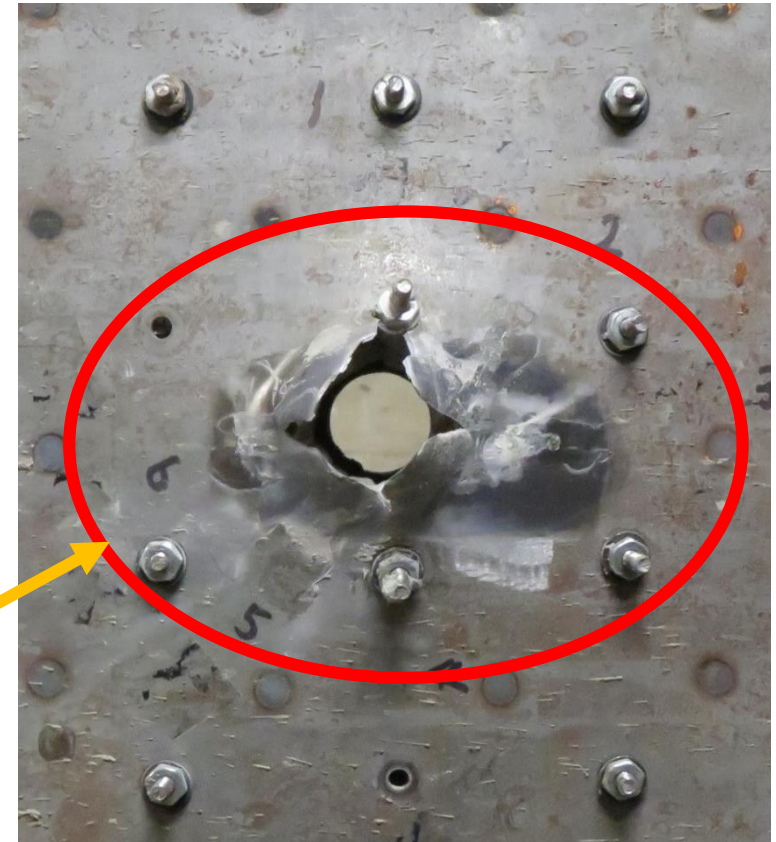
Gr.1, Specimen #7 : 3-0.53-50-1-2-513



Front Plate



Rear Plate



Failure mode

3. 소규모 실험결과

Accuracy of the three-step method and its conservatism

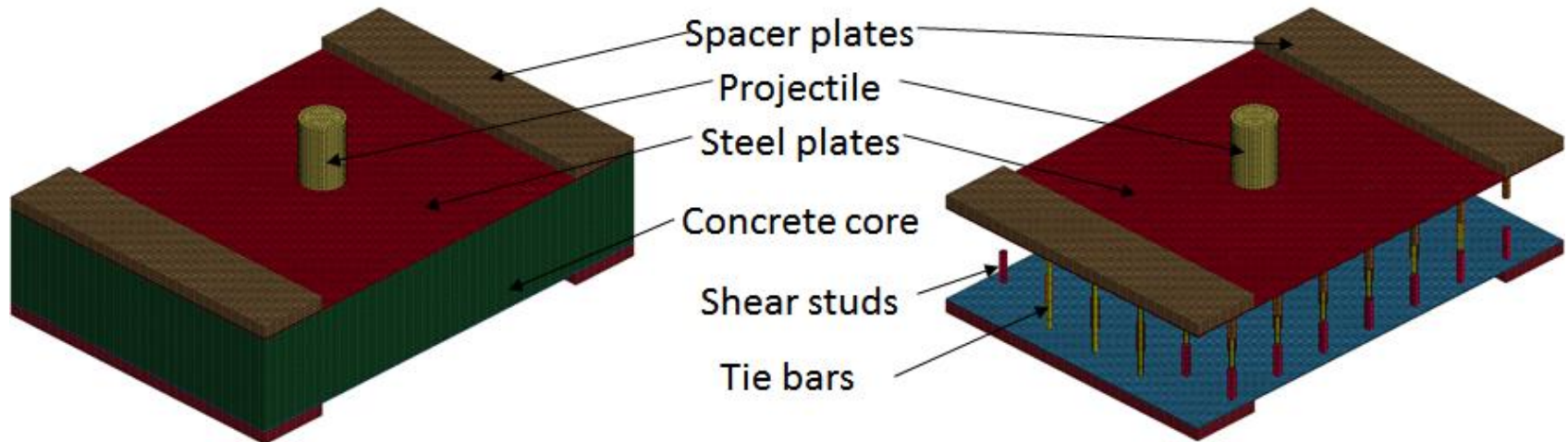
- ❖ 16 SC specimens are tested with observations of **Stopped/Perforated, Penetration depth, Bulging depth.**
- ❖ All specimens are **stopped** for impact velocities less than **15%** times the AISC design velocity.
- ❖ Only three specimens are perforated for impact velocities greater than **33%** times the AISC design vel.

소규모 충돌실험 결과

Test group	Test specimen	Projectile			Expected result	Test result	Damage mode	V_{des} (ft/s)	V_{imp}/V_{des}	Penetration depth (in)	Penetration depth / Wall thickness	Rear faceplate bulging (in)
		Weight (lb)	Diameter (Nominal, in)	V_{imp} (ft/s)								
	1 3-0.37-50-1.0-1.3-554	1.316	1.0	593	Stopped	Stopped	Bulging	615	0.964	2.25	0.56	0.25
	2 3-0.37-50-1.0-1.3-677	1.301	1.0	674	Perforated	Stopped	Bulging	615	1.096	3.25	0.81	0.63
	3 3-0.37-50-1.0-2.0-430	1.991	1.0	424	Stopped	Stopped	Bulging	479	0.885	1.69	0.42	0.25
	4 3-0.37-50-1.0-2.0-525	2.000	1.0	513	Perforated	Stopped	Bulging	479	1.071	3.16	0.79	0.58
Gr. 1	5 3-0.53-50-1.5-1.3-660	1.303	1.5	667	Stopped	Stopped	Bulging	729	0.915	1.44	0.36	0.56
	6 3-0.53-50-1.5-1.3-750	1.301	1.5	760	Perforated	Stopped	Bulging	729	1.043	2.19	0.55	0.72
	7 3-0.53-50-1.0-2.0-513	2.000	1.0	640	Perforated	Perforated	Perforation	479	1.336	-	-	-
	8 3-0.53-50-1.0-2.0-626	1.991	1.0	710	Perforated	Perforated	Perforation	479	1.482	-	-	-
	9 3-1.23-50-1.5-3.5-380	3.521	1.5	550	Perforated	Stopped	Splitting	422	1.303	4.13	1.03	1.63
	10 3-1.23-50-1.5-3.5-465	3.541	1.5	489	Perforated	Stopped	Bulging	422	1.159	2.03	0.51	0.59
Gr. 2	1 5-0.48-50-1.0-2.0-445	1.997	1.0	467	Stopped	Stopped	Bulging	495	0.943	2.25	0.56	0.28
	2 5-0.48-50-1.0-2.0-544	1.997	1.0	549	Perforated	Stopped	Splitting	495	1.109	3.50	0.88	0.75
	3 5-0.48-50-1.5-3.5-408	3.512	1.5	410	Stopped	Stopped	Bulging	453	0.905	1.50	0.38	0.38
	4 5-0.48-50-1.5-3.5-498	3.534	1.5	484	Perforated	Stopped	Bulging	453	1.068	2.63	0.66	0.69
Gr. 3	1 3-0.37-65-1.0-2.0-443	2.008	1.0	539	Perforated	Stopped	Bulging	492	1.096	3.13	0.78	0.69
	2 3-0.37-65-1.0-2.0-541	2.006	1.0	634	Perforated	Perforated	Perforated	492	1.289	-	-	-

Numerical model

- Finite element code : LS-DYNA
- **Concrete** → *MAT_WINFRITH (Solid, Reduced integration)
 - Erosion analytically determined.
 - Strain rate effects : default in Winfrith
- **Steel plates** → *MAT_PIECEWISE_PLASTICITY with true stress & strain
 - Strain rate effects per UFC 3-340-02 (DoD 2008)
- **Tie & Stud** → Beam element, stud slip behavior using Zero-length discrete beam element
 - Others similar to steel plates



3. 소규모 실험결과

Parametric Study

○ Conservatism of AISC design eq.

- ✓ Gr.1, d=1.0in: **15% to 25%** conservative
- ✓ Gr.1, d=1.5in: **10% to 30%** conservative
- ✓ Gr.2, d=1.0in: **7% to 15%** conservative
- ✓ Gr.2, d=1.5in: **10% to 16%** conservative
- ✓ Gr.3, d=1.0in: **12% to 17%** conservative

10% to 21%, in a mean sense, conservative

These results are to be used to propose and verify a new design equation

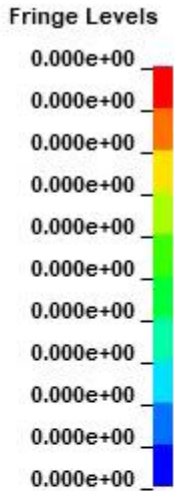
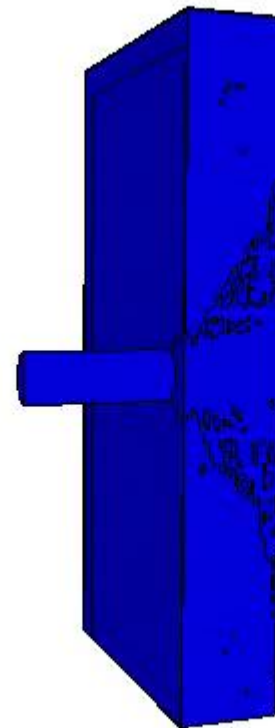
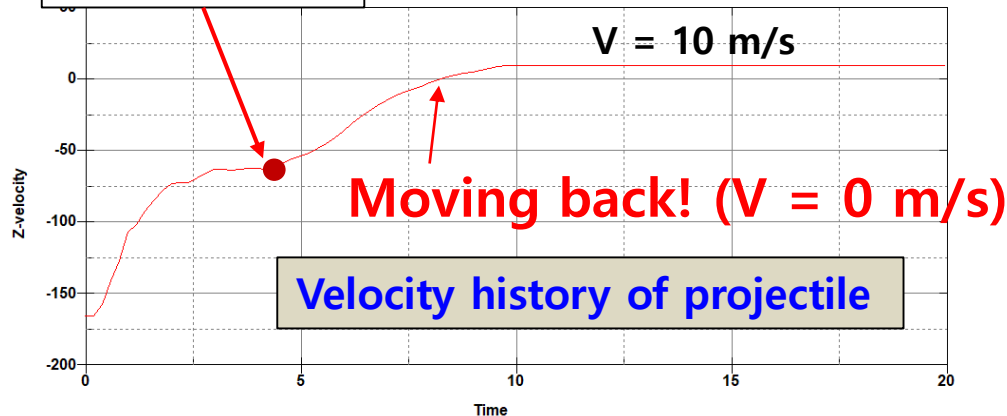
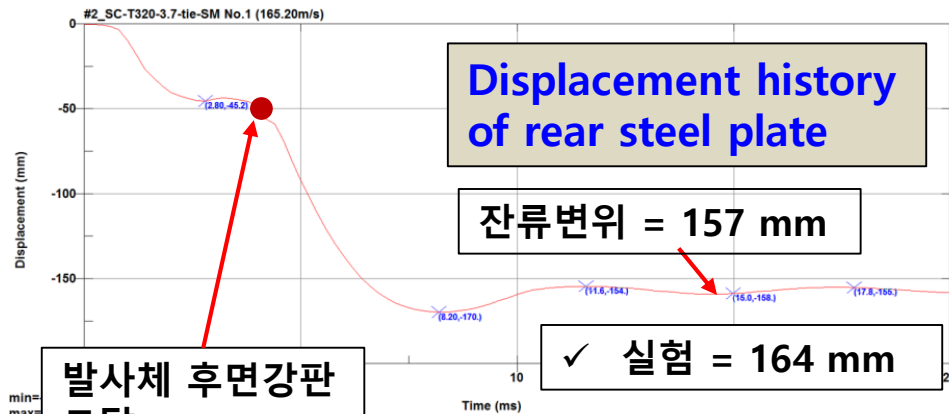
Anal ysis Gr.	Anal ysis No.	Analysis Identifier	V_{imp} (ft/s)	V_{dc} (ft/s)	V_{imp}/V_{dc}	FEA Result	Damage mode	$X_{c,FEM}$ (in)	$X_{bg,FEM}$ (in)
Gr.1	1	3-0.37-50-1.0-1.3-745	745	613	1.215	Stopped	Bulging	3.66	0.81
	2	3-0.37-50-1.0-1.3-770	770	613	1.256	Perforated	Perforation	-	-
	3	3-0.37-50-1.0-1.3-800	800	613	1.305	Perforated	Perforation	-	-
	4	3-0.37-50-1.0-2.0-528	528	485	1.089	Stopped	Bulging	3.29	0.48
	5	3-0.37-50-1.0-2.0-540	540	485	1.113	Stopped	Splitting	4.01	-
	6	3-0.37-50-1.0-2.0-558	558	485	1.151	Perforated	Perforation	-	-
	7	3-0.53-50-1.5-1.3-875	875	732	1.195	Stopped	Bulging	3.01	0.93
	8	3-0.53-50-1.5-1.3-912	912	732	1.246	Stopped	Splitting	3.83	1.65
	9	3-0.53-50-1.5-1.3-950	950	732	1.298	Perforated	Perforation	-	-
	10	3-0.53-50-1.5-2.0-667	667	582	1.146	Stopped	Bulging	3.43	1.17
	11	3-0.53-50-1.5-2.0-690	690	582	1.186	Stopped	Bulging	3.89	1.31
	12	3-0.53-50-1.5-2.0-710	710	582	1.220	Perforated	Perforation	-	-
	13	3-0.53-50-1.5-2.0-728	728	582	1.251	Perforated	Perforation	-	-
	14	3-0.53-50-1.5-2.0-757	757	582	1.301	Perforated	Perforation	-	-
	15	3-0.53-50-1.0-2.0-528	528	485	1.089	Stopped	Bulging	3.53	0.46
	16	3-0.53-50-1.0-2.0-540	540	485	1.113	Stopped	Splitting	4.06	-
	17	3-0.53-50-1.0-2.0-558	558	485	1.151	Perforated	Perforation	-	-
	18	3-0.53-50-1.0-2.0-577	577	485	1.190	Perforated	Perforation	-	-
	19	3-0.53-50-1.0-2.7-455	455	413	1.102	Stopped	Bulging	3.21	0.60
	20	3-0.53-50-1.0-2.7-475	475	413	1.150	Stopped	Bulging	3.59	0.69
	21	3-0.53-50-1.0-2.7-495	495	413	1.199	Perforated	Perforation	-	-
	22	3-0.53-50-1.0-3.5-395	395	359	1.100	Stopped	Bulging	3.27	0.64
	23	3-0.53-50-1.0-3.5-413	413	359	1.150	Stopped	Splitting	3.72	(Elem. Del.)
	24	3-0.53-50-1.0-3.5-430	430	359	1.198	Perforated	Perforation	-	-
	25	3-1.23-50-1.5-3.5-465	465	432	1.076	Stopped	Splitting	3.76	-
	26	3-1.23-50-1.5-3.5-477	477	432	1.104	Perforated	Perforation	-	-
Gr.2	1	5-0.48-50-1.0-2.0-528	528	504	1.048	Stopped	Splitting	3.50	-
	2	5-0.48-50-1.0-2.7-450	450	429	1.049	Stopped	Bulging	3.02	(Elem. Del.)
	3	5-0.48-50-1.0-2.7-467	467	429	1.089	Stopped	Bulging	3.21	(Elem. Del.)
	4	5-0.48-50-1.0-2.7-475	475	429	1.107	Stopped	Bulging	3.35	(Elem. Del.)
	5	5-0.48-50-1.0-2.7-495	495	429	1.154	Perforated	Perforation	-	-
	6	5-0.48-50-1.5-3.5-506	506	465	1.088	Stopped	Splitting	4.48	-
	7	5-0.48-50-1.5-3.5-528	528	465	1.135	Perforated	Perforation	-	-
	8	5-0.48-50-1.5-2.0-690	690	625	1.104	Stopped	Splitting	4.17	-
	9	5-0.48-50-1.5-2.0-710	710	625	1.136	Perforated	Perforation	-	-
Gr.3	1	3-0.37-65-1.0-2.0-558	558	500	1.116	Stopped	Bulging	3.62	0.53
	2	3-0.37-65-1.0-2.0-568	568	500	1.136	Perforated	Perforation	-	-
	3	3-0.37-65-1.0-2.0-577	577	500	1.154	Perforated	Perforation	-	-
	4	3-0.37-65-1.0-2.7-475	475	425	1.118	Stopped	Splitting	3.74	-
	5	3-0.37-65-1.0-2.7-495	495	425	1.165	Perforated	Perforation	-	-

4. 실증실험기반 해석적 평가

Simulation Results

실험체 No. 2 (SC-T320-3.7-tie)

- $V = 165 \text{ m/s}$, 결과 : 미관통



Simulation Video

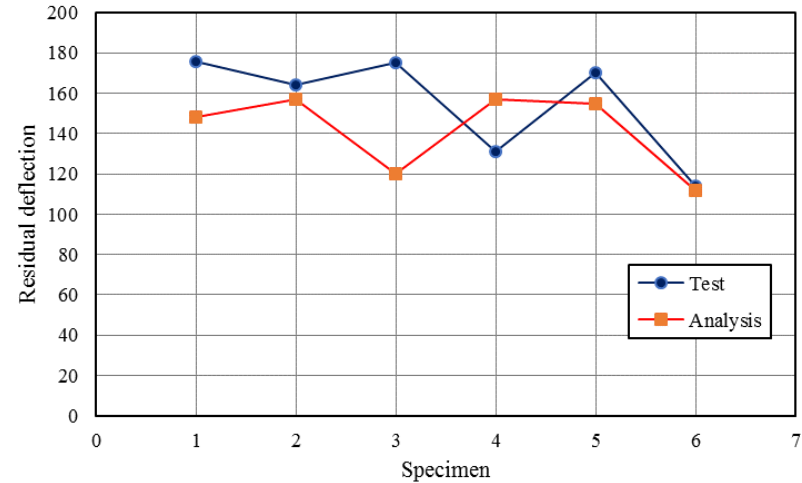
4. 실증실험기반 해석적 평가

Validation

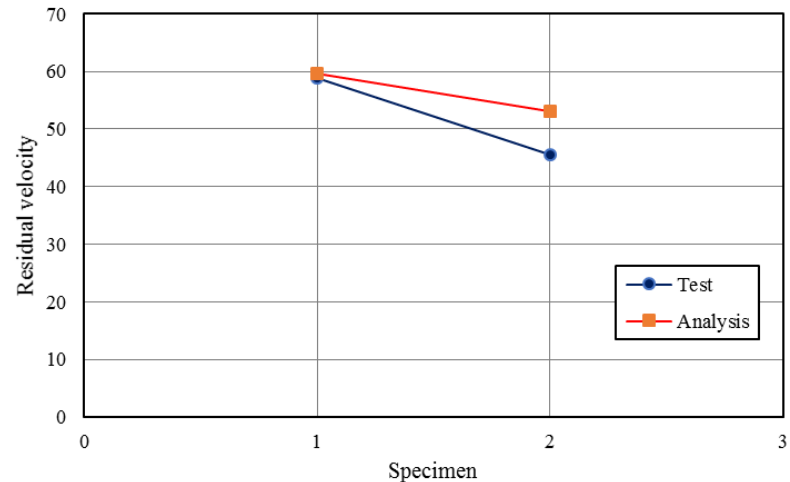
Stopped/Perforated

Test summary			실험	해석
No	Specimen ID	V		
		Test	Perforated / Stopped	Perforated / Stopped
		(m/s)		
1	SC-T320-3.7-SM	165.3	Stopped	Stopped
		-	-	-
2	SC-T320-3.7-tie-SM	165.2	Stopped	Stopped
		180	Perforated	Perforated
3	SC-T480-3.7-SM	197.5	Stopped	Perforated
		224.2	Perforated	Perforated
4	SC-T240-5.0-SM	203	Perforated	Perforated
		178.5	Stopped	Stopped
5	SC-T360-5.0-SM	180	Stopped	Stopped
		198.5	Stopped	Stopped
6	SC-T360-5.0-tie-SM	179.3	Stopped	Stopped
		-	-	-
7	SC-T360-5.0-HSA	167.6	Perforated	Perforated
		-	Stopped	-
8	RC-T320-3.7	142.6	Perforated	Perforated
		105	Stopped	Stopped

Residual deflection



Residual velocity



Thank you for your attention!