sustainability

Supplemendary material to the paper:

Minimally invasive retrofitting of RC joints with externally applied SMA plate - adaptive design optimisation through probabilistic damage simulation

Mohammad Amin Molod, Franz-Joseph Barthold, and Panagiotis Spyridis

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1. Model input data – Constitutive material laws

Parameter type	Parameter subtype	Parameter	Property	Range	Unit	Value
Elasticity	-	E	Young modulus	-	GPa	36.57
	-	v	Poissons' ratio	-	-	0.2
Plasticity	Drucker-Prager yield function	f_{uc}	Uniaxial compressive strength	$f_{uc} \geq f_{ut}$	MPa	53.5
		f_{bc}	Biaxial compressive strength	$f_{bc} \geq f_{uc}$	MPa	61.525
		f_{ut}	Uniaxial tensile strength	$f_{ut} \geq 0$	MPa	3.5
	Compression cap	$\sigma^C{}_V$	Intersection point abscissa between compression cap and Drucker-Prager yield function	$\sigma^C{}_V \geq f\,uc/3$	MPa	-60
		R	Ratio between the major and minor axes of the cap	$R \geq 0$	-	2
	Hardening	D	Hardening material constant	$D \geq 0$	MPa	5.50E+04
		R_T	Tension cap hardening	$R_T \geq 0$	-	4
Damage	-	Υ_{t0}	Tension damage threshold	$\Upsilon_{t0} \geq 0$	-	0
	-	Υ_{c0}	Compression damage threshold	$\Upsilon_{c0} \geq 0$	-	2.00E-06
	-	β_t	Tension damage evolution constant	$\beta_t \geq 0$	-	7.00E+03
	-	β_c	Compression damage evolution constant	$\beta_c \geq 0$	-	5.00E+03
Nonlocal	-	c	Nonlocal interaction range parameter	c ≥ 0	mm^2	2550
	-	m	Over-nonlocal averaging parameter	m ≥ 0	-	2.5

Table 1. Required parameters to define coupled damage-plasticity microplane model

Parameter type	Parameter	Property	Range	Unit	Value
Elasticity	E	Young modulus	-	GPa	36.57
	v	Poissons' ratio	-	-	0.2
Material constants	β_t	Shear transfer coefficients for an open crack	$1 \geq \beta_t \geq 0$	-	0.3
	β_c	Shear transfer coefficients for a closed crack	$1 \geq \beta_c \geq 0$	-	0.7
	f_t	Uniaxial tensile cracking stress	$f_t \geq 0$	MPa	3.5
	f_c	Uniaxial crushing stress (positive)	$f_c \geq f_t$	MPa	53.5
	f_{cb}	Biaxial crushing stress (positive)	f_{cb} (=1.2 fc) $\geq f_c$	MPa	0
	$\sigma^a{}_h$	Ambient hydrostatic stress state	$\sqrt{3}\, f_c \geq \sigma^a{}_h$	MPa	0
	f_1	Biaxial crushing stress (positive) under the ambient hydrostatic stress state	f_1 (=1.45 f_c) $\geq f_{cb}$	MPa	0
	f_2	Uniaxial crushing stress (positive) under the ambient hydrostatic stress state	f_2 (=1.725 fc) $\geq f_1$	MPa	0
	T_c	Stiffness multiplier for cracked tensile condition	$1 \geq T_c \geq 0$	-	0.6

Table 2. Required parameters to define Menetrey-William constitutive model

Parameter type	Parameter	Property	Range	Unit	Value
Elasticity	E	Young modulus	-	GPa	36.57
	v	Poissons' ratio	-	-	0.2
Material constants	k_0	Damage function constant 1	-	-	0.779
	k_1	Damage function constant 2	-	-	0.779
	k_2	Damage function constant 3	-	-	0.136
	$\Upsilon^{mic}{}_0$	Critical equivalent strain	-	-	4.18E-05
	α^{mic}	Maximum damage parameter	-	-	0.1
	β^{mic}	Scale for rate of damage	$1 \geq \beta^{mic} \geq 0$	-	2.00E+04
	c	Nonlocal interaction range parameter	√c /2 ≥ Elem. Size	-	2550

Table 3. Required parameters to define elastic microplane material model

2. **Model input data – Element types**

(adopted from Ansys Mechanical APDL Documentation 2019 by ANSYS Inc.)

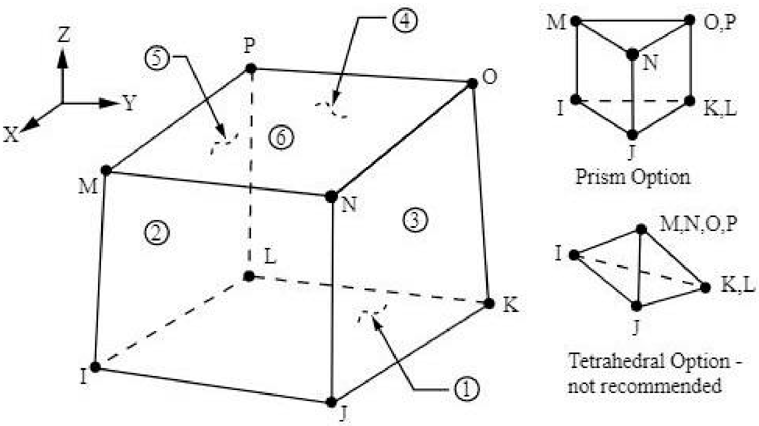


Fig 1. Solid element CPT 215

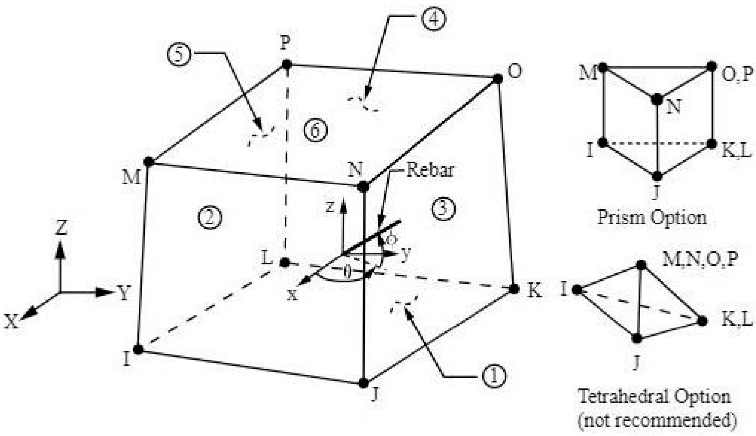


Fig 2. Solid element 65

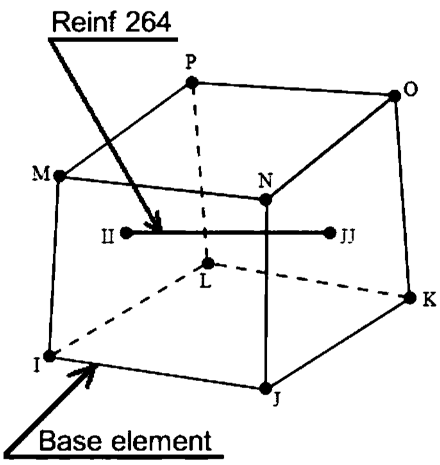


Fig 3. Reinf264

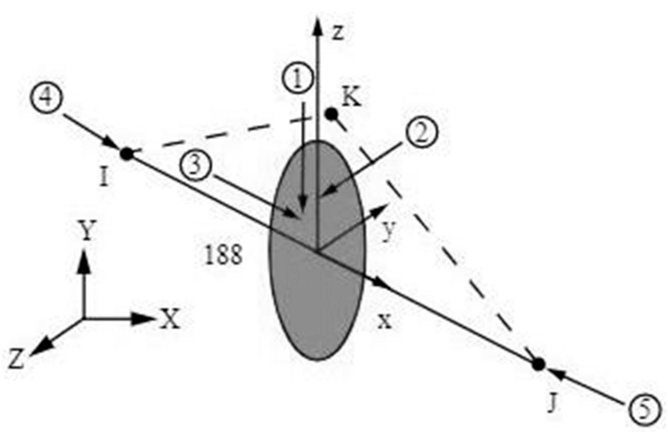


Fig 4. Beam 188

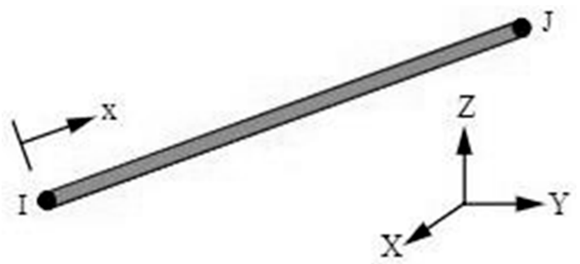
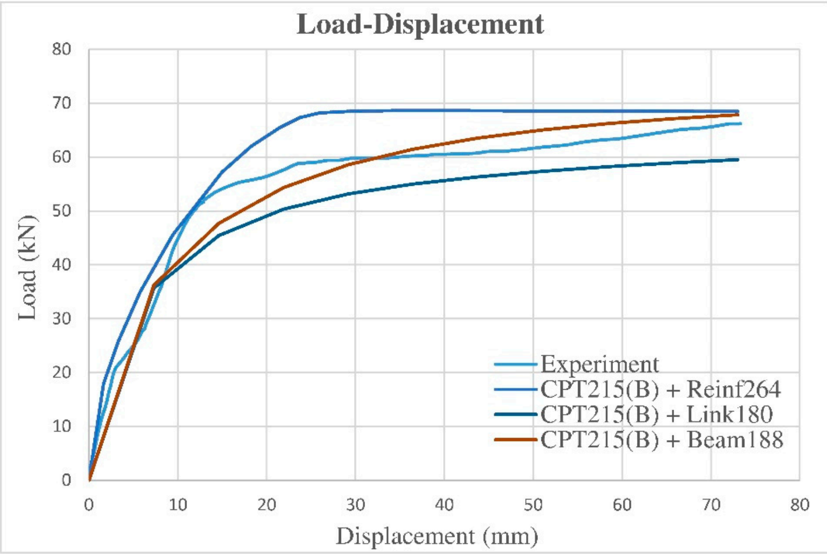
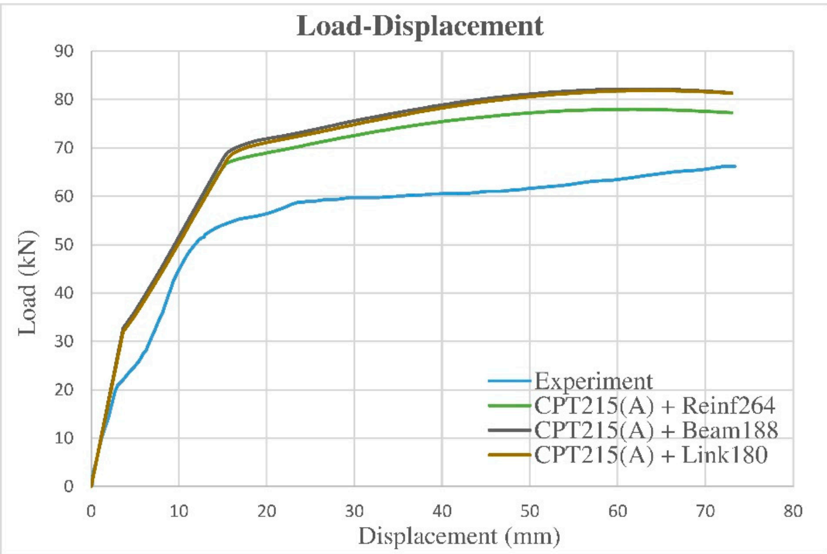
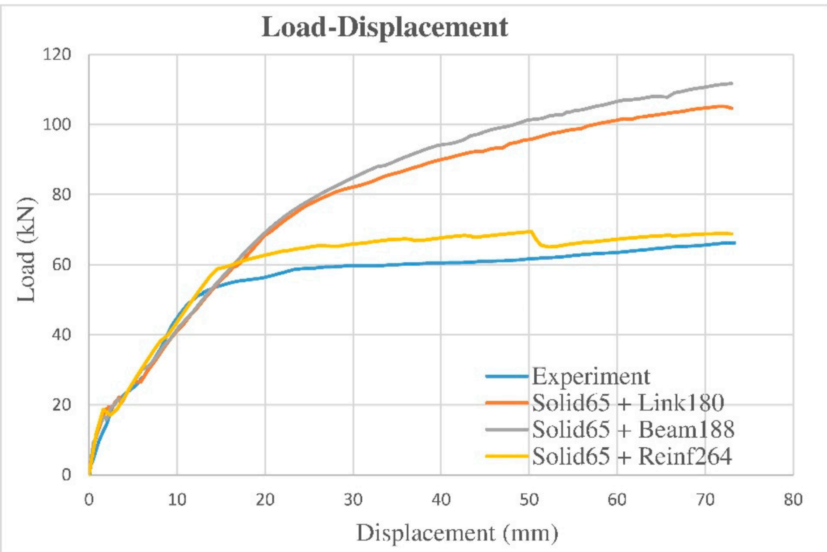


Fig 5. Link180

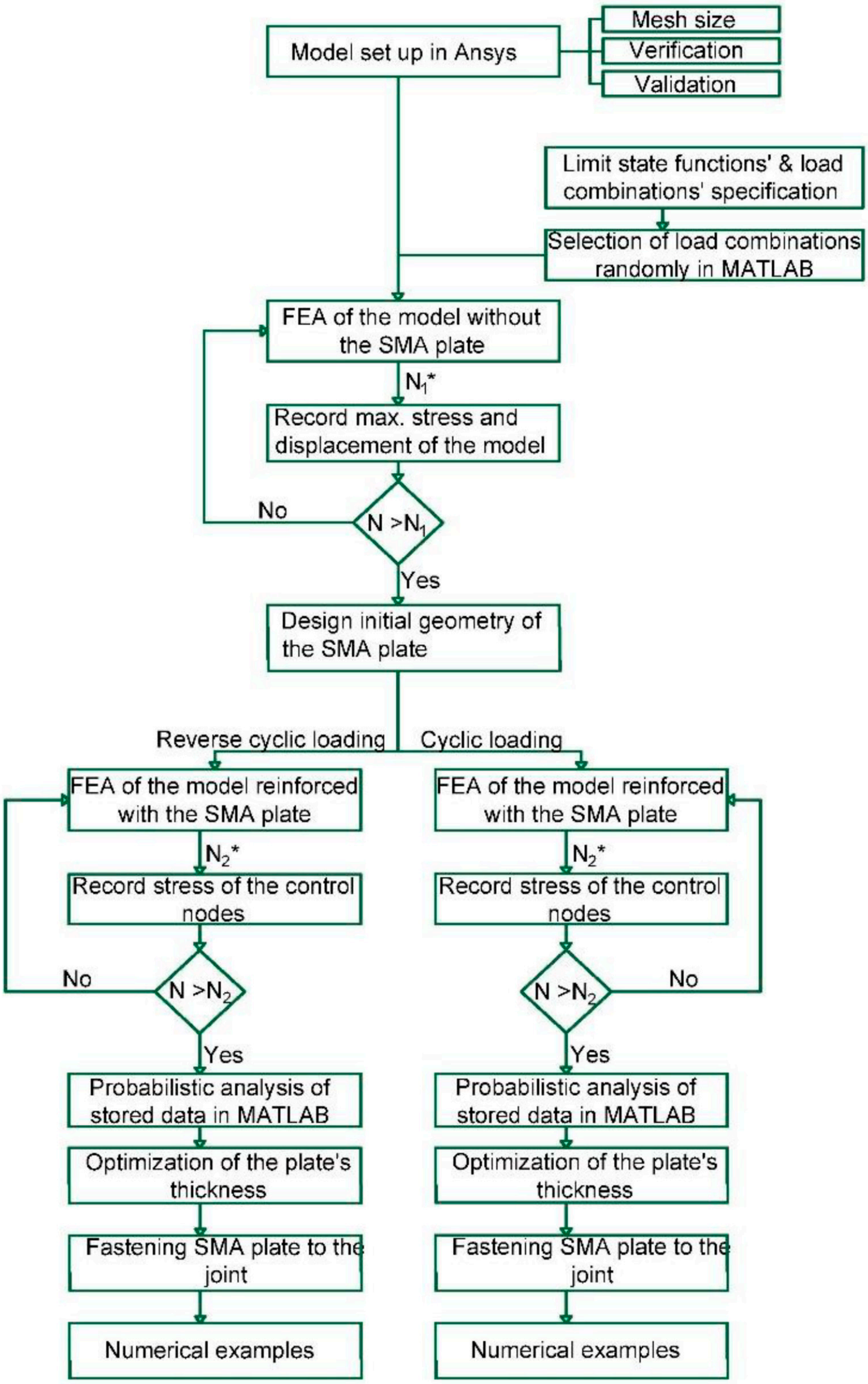
3. Load-displacement curves from experiment and models with different elements combinations







4. Algorithm flow chart



5. Table of symbols and notations

E	Young modulus
ν	Poissons' ratio
ρ	Density
f_{uc}	Uniaxial compressive strength
f_{bc}	Biaxial compressive strength
f_{ut}	Uniaxial tensile strength
$\sigma^{C}{}_{V}$	Intersection point abscissa between compression cap and Drucker-Prager yield function
R	Ratio between the major and minor axes of the cap
D	Hardening material constant
R_T	Tension cap hardening
Υ_{t0}	Tension damage threshold
Υ_{c0}	Compression damage threshold
β_t	Tension damage evolution constant
β_c	Compression damage evolution constant
c	Nonlocal interaction range parameter
m	Over-nonlocal averaging parameter
k_0	Damage function constant 1
k_1	Damage function constant 2
k_2	Damage function constant 3
$\Upsilon^{mic}{}_0$	Critical equivalent strain
α^{mic}	Maximum damage parameter
β^{mic}	Scale for rate of damage
c	Nonlocal interaction range parameter
β_t	Shear transfer coefficients for an open crack
β_c	Shear transfer coefficients for a closed crack
f_t	Uniaxial tensile cracking stress
f_c	Uniaxial crushing stress (positive)
f_{cb}	Biaxial crushing stress (positive)
$\sigma^a{}_h$	Ambient hydrostatic stress state
f_1	Biaxial crushing stress (positive) under the ambient hydrostatic stress state
f_2	Uniaxial crushing stress (positive) under the ambient hydrostatic stress state
T_c	Stiffness multiplier for cracked tensile condition
$\sigma_s{}^{AS}$	Starting stress value for the forward phase transformation
$\sigma_f{}^{AS}$	Final stress value for the forward phase transformation
$\sigma_s{}^{SA}$	Starting stress value for the reverse phase transformation
$\sigma_f{}^{SA}$	Final stress value for the reverse phase transformation
e_L	Maximum residual strain
α	Parameter measuring the difference between material responses in tension and compression

σ_y	Yield stress
σ_u	Ultimate stress
ε_{su}	Ultimate strain of steel
ε_{cu}	Ultimate strain of concrete
ε_s	Strain of steel
ε_c	Strain of concrete
ξ	Factor defining the effective height of the compression zone
x	distance of the neutral axis from the extreme compression fiber
d	Distance between top surface of a beam and middle of bottom reinforcement
a	Distance between top surface of a beam and middle of top reinforcement
z	Depth of beam
b	Width of beam cross-section
α_R	Factor defining the effective strength of concrete
F_{cd}	Compressive carrying load capacity of concrete
F_{sd}	Compressive carrying load capacity of steel
σ_{cd}	Design stress of concrete
σ_{sd}	Design stress of steel
A_{s1}	Area of top steel reinforcement (compression rebar)
A_{s2}	Area of bottom steel reinforcement (tensile rebar)
F_{ud}	Ultimate design load
K_a	Coefficient
M_{Rd}	Moment capacity of the section
R_1	Axial column force
R_2	Bending moment force
R_3	Axial beam force
D_b	Steel bar diameter
L_p	Length of plastic hinge region