Validated leaf spring suspension models

PhD Public defence

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UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
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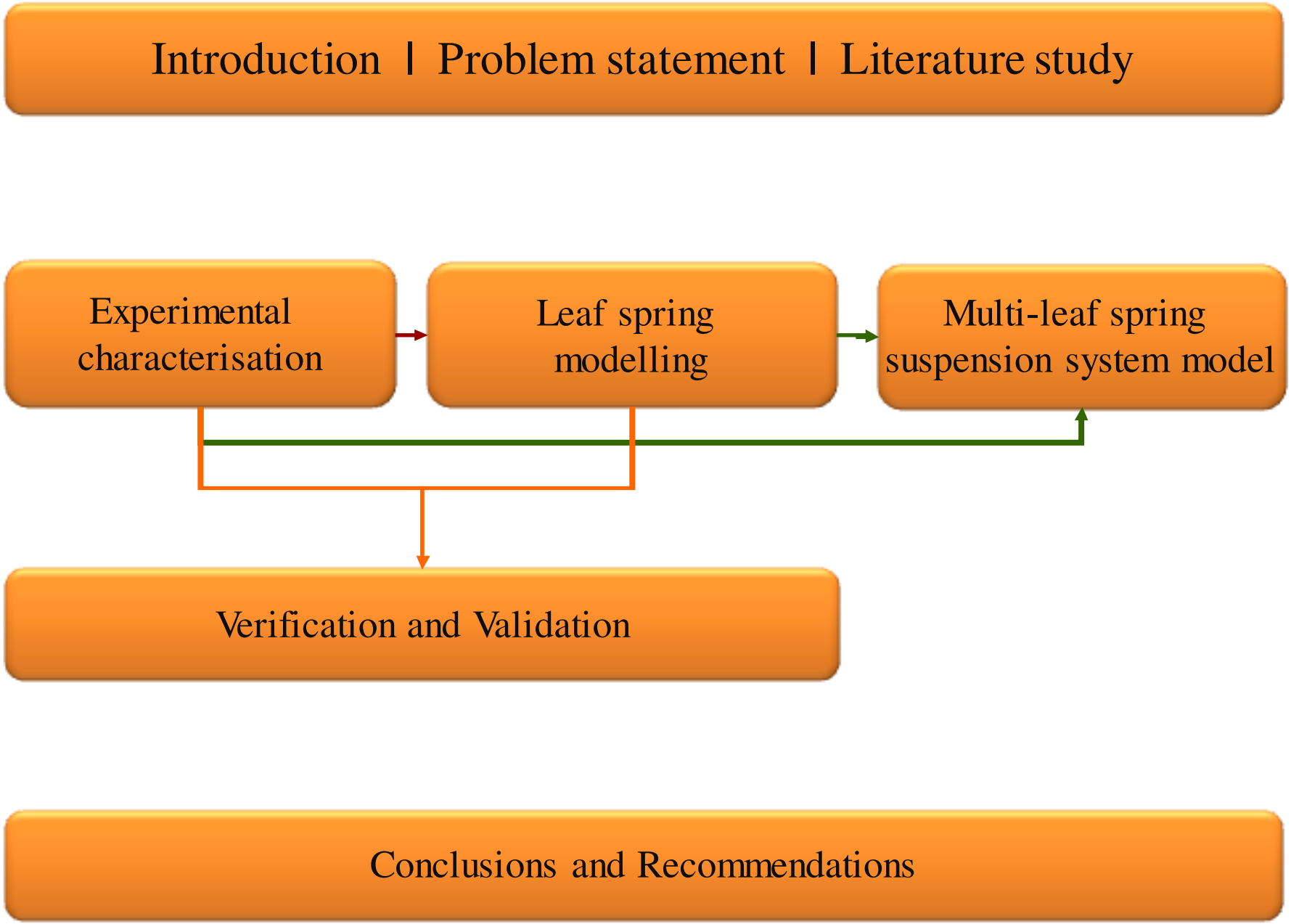
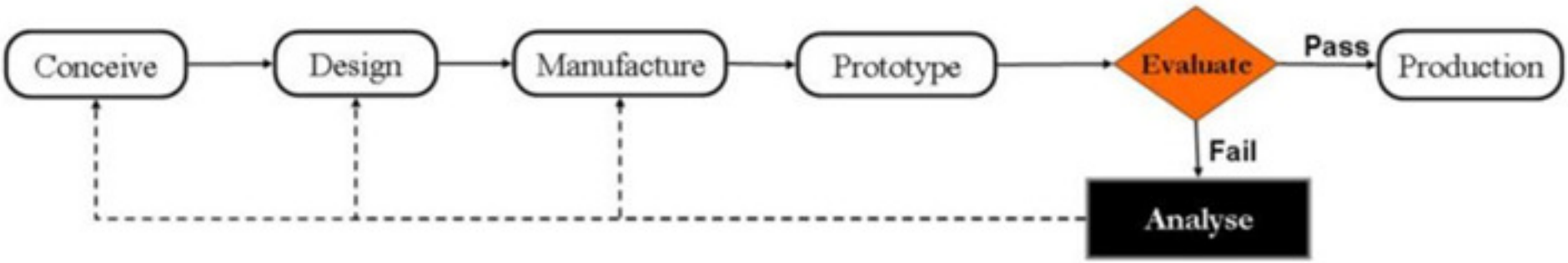
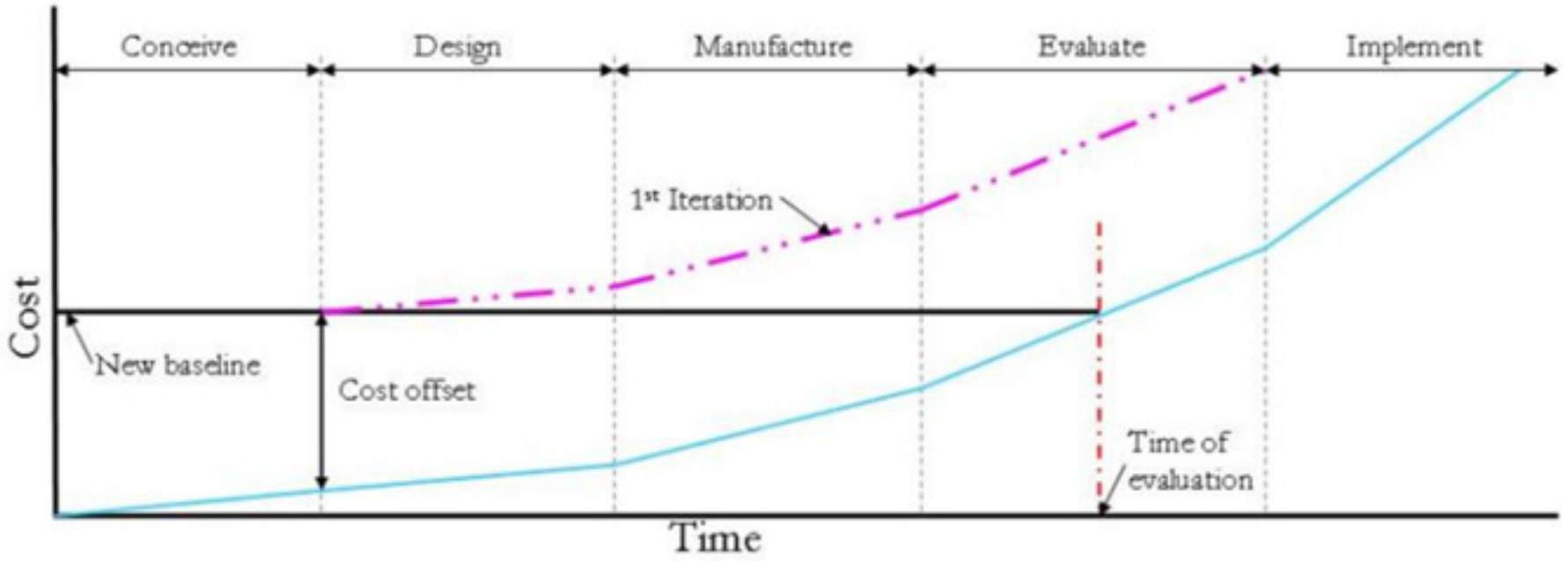
FACULTY OF ENGINEERING, THE BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY (EBIT)


Opportunity…
Support…

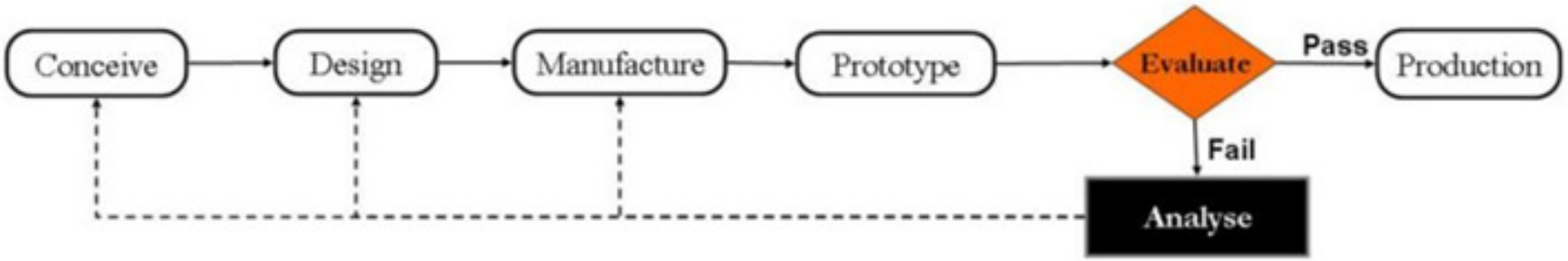

Introduction | Problem statement | Literature study
Experimental characterisation
Leaf spring modelling
Multi-leaf spring suspension system model
Verification and Validation
Conclusions and Recommendations

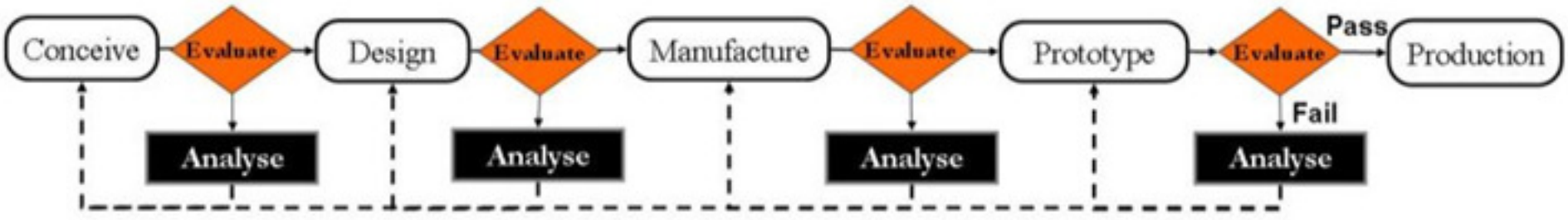
Introduction





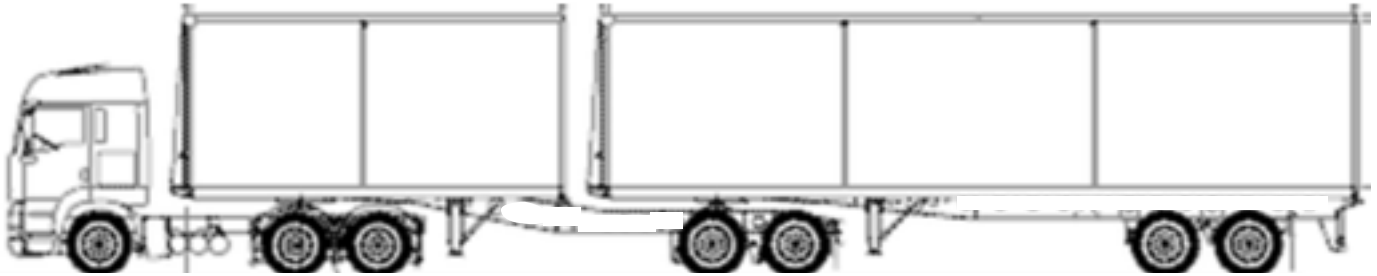
Introduction



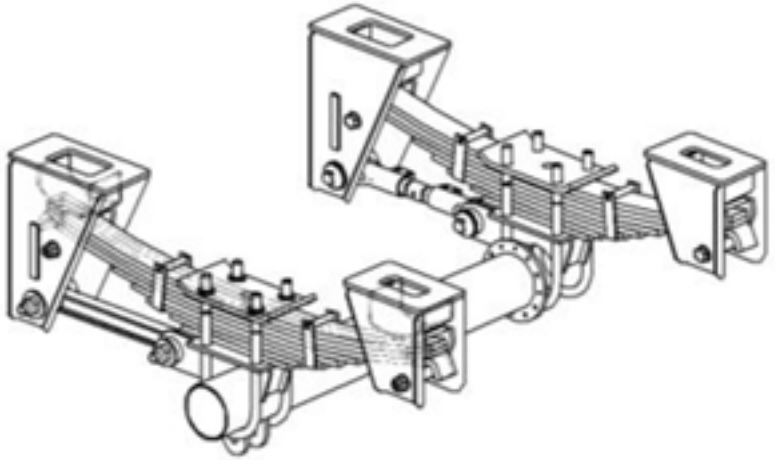


Problem statement

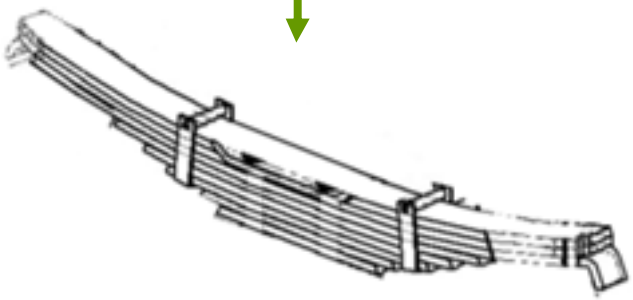
System
(Vehicle)

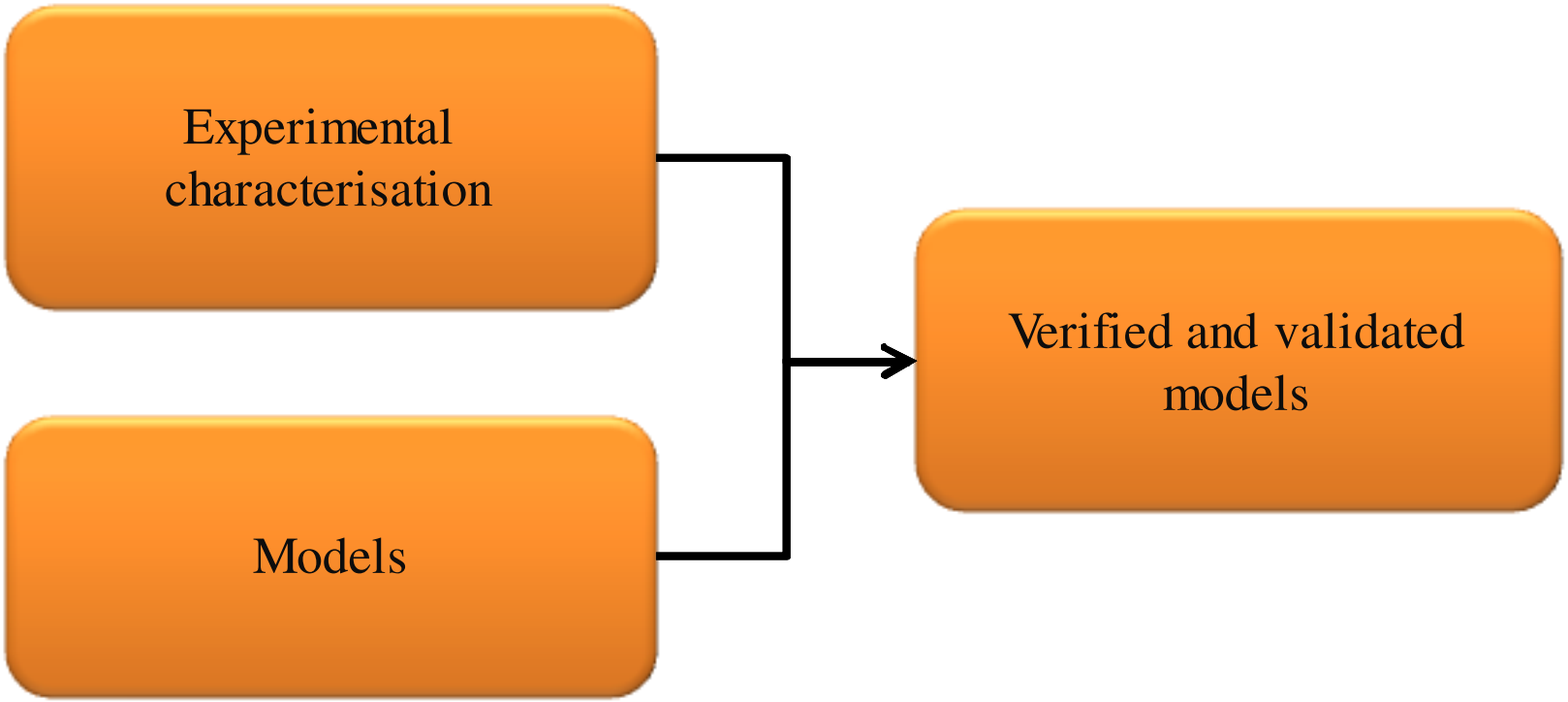


Subsystem
(Suspension system)

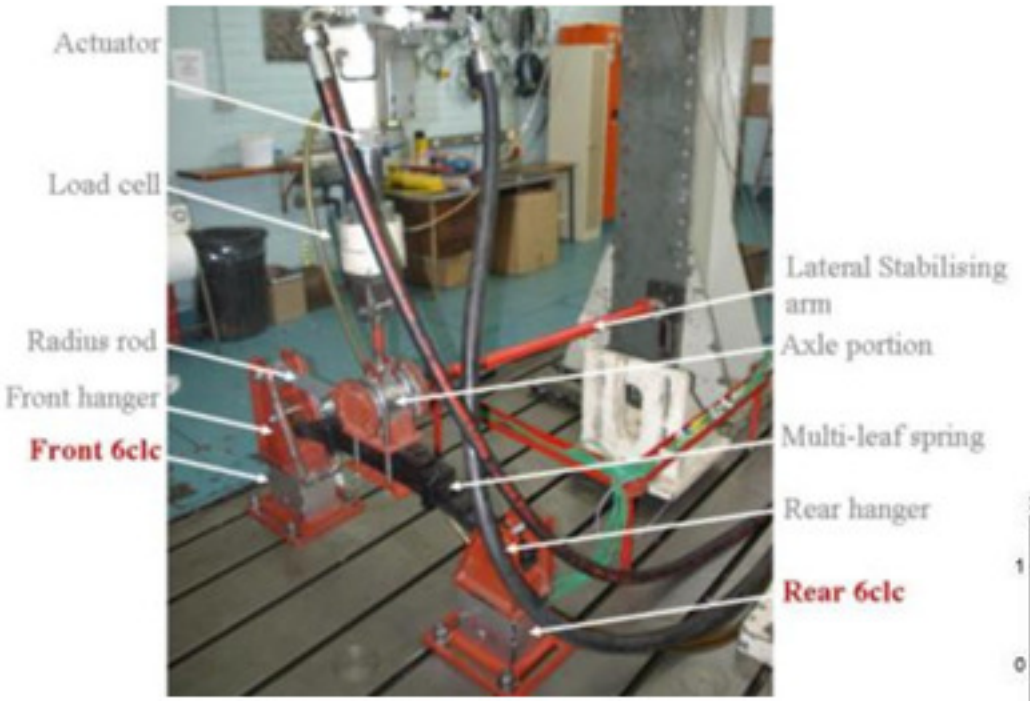


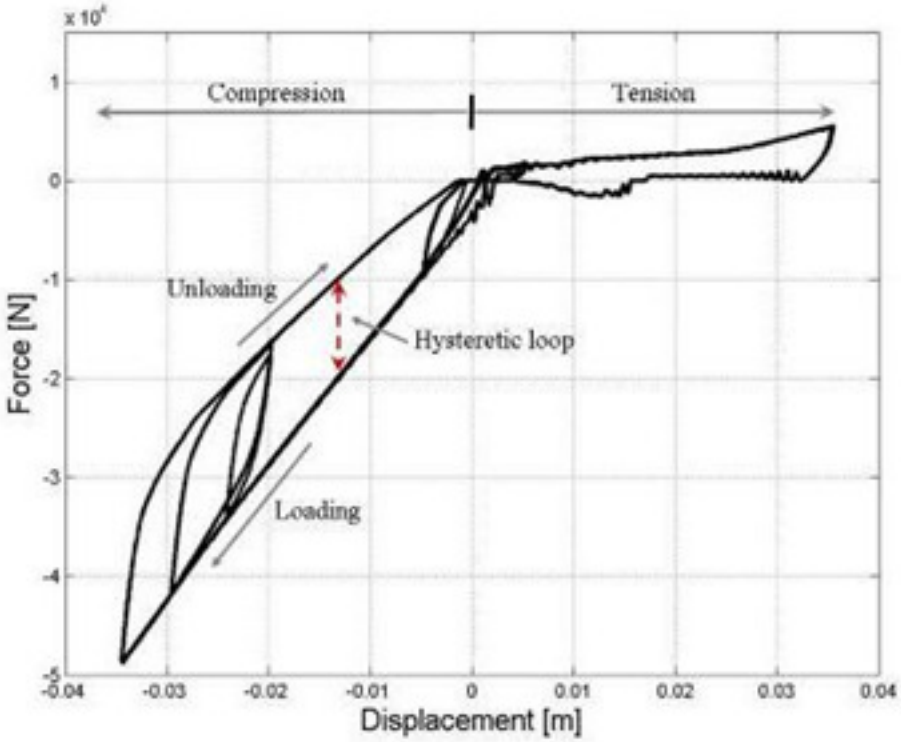
Component
(Leaf spring)



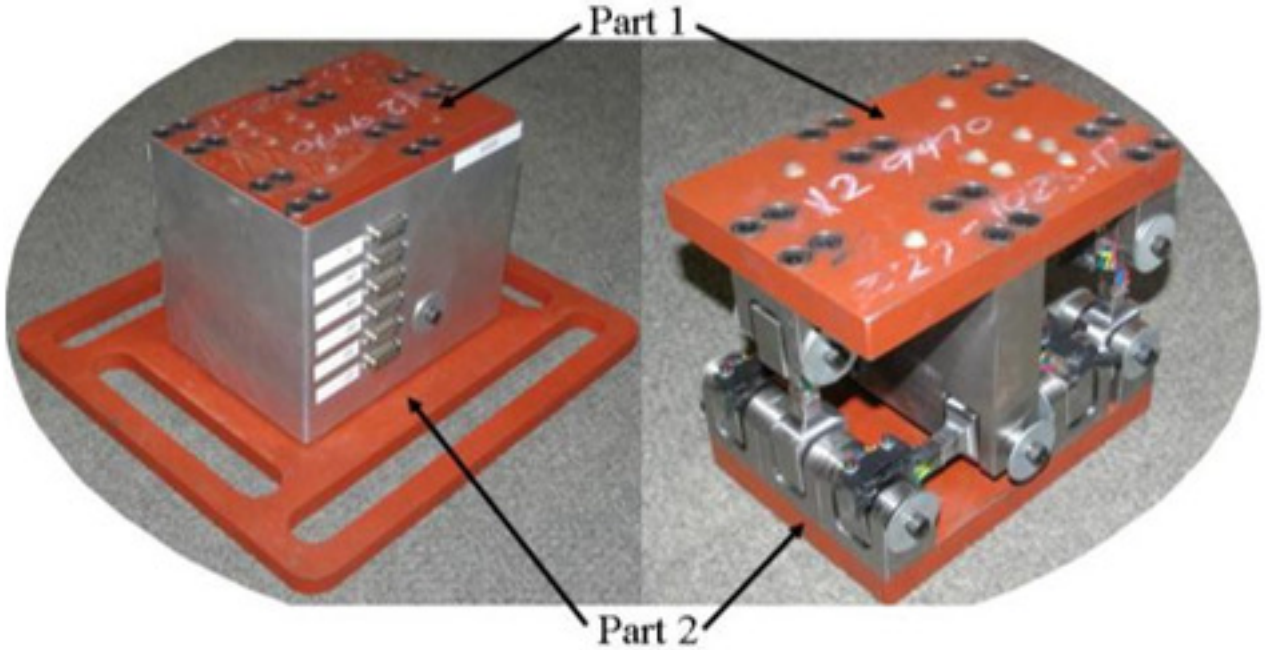

Experimental characterisation
Models
Verified and validated models

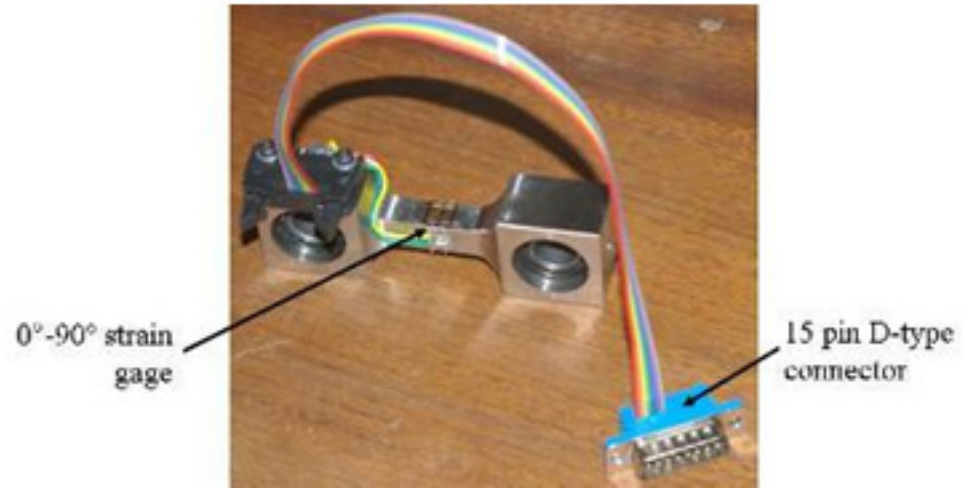
Experimental characterisation



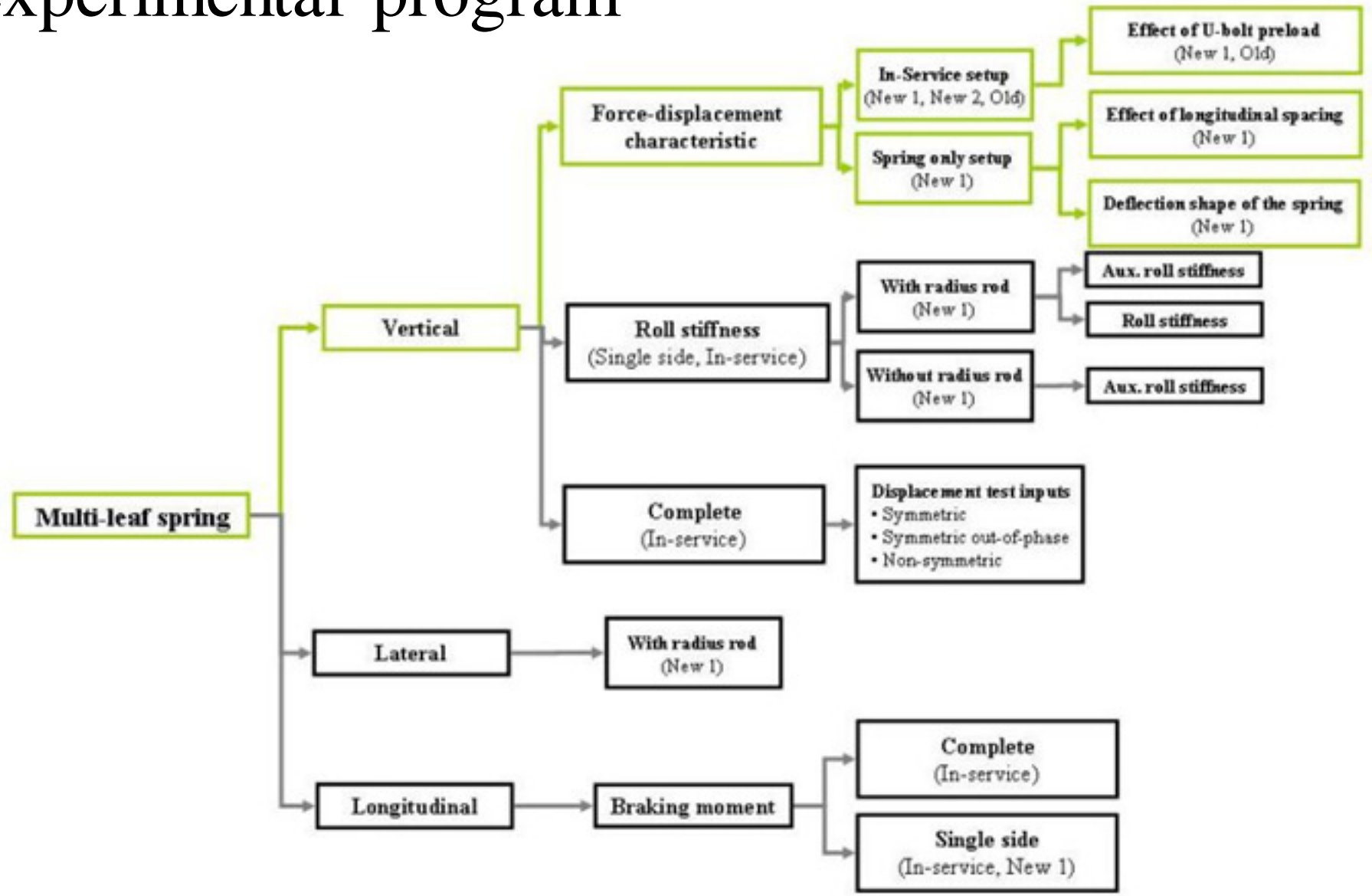


Six component load cell

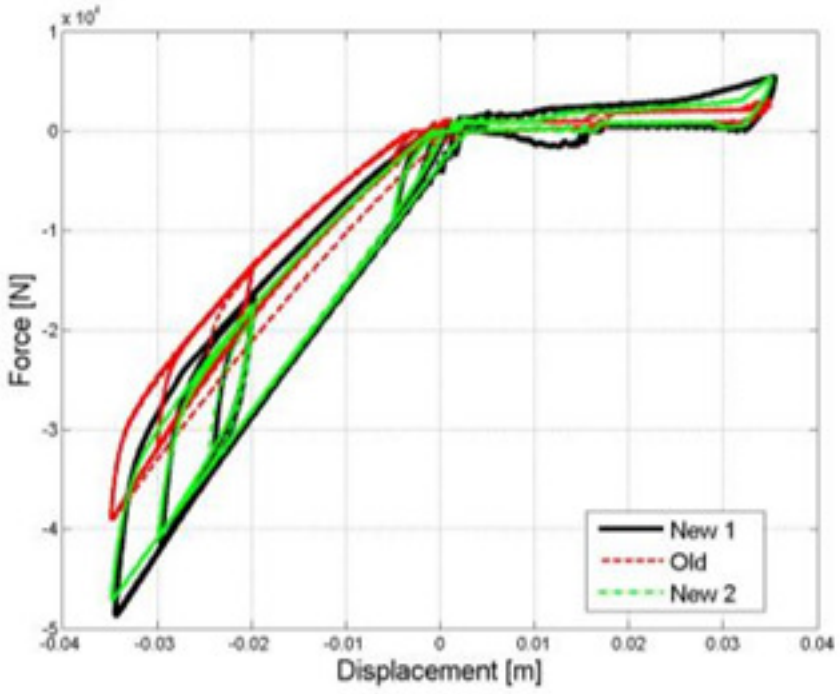


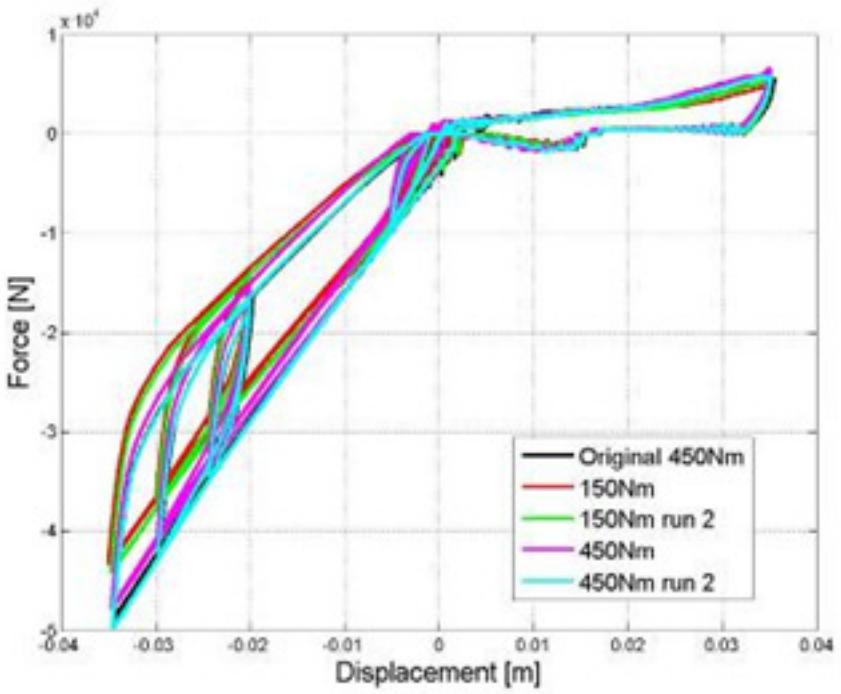


Experimental program

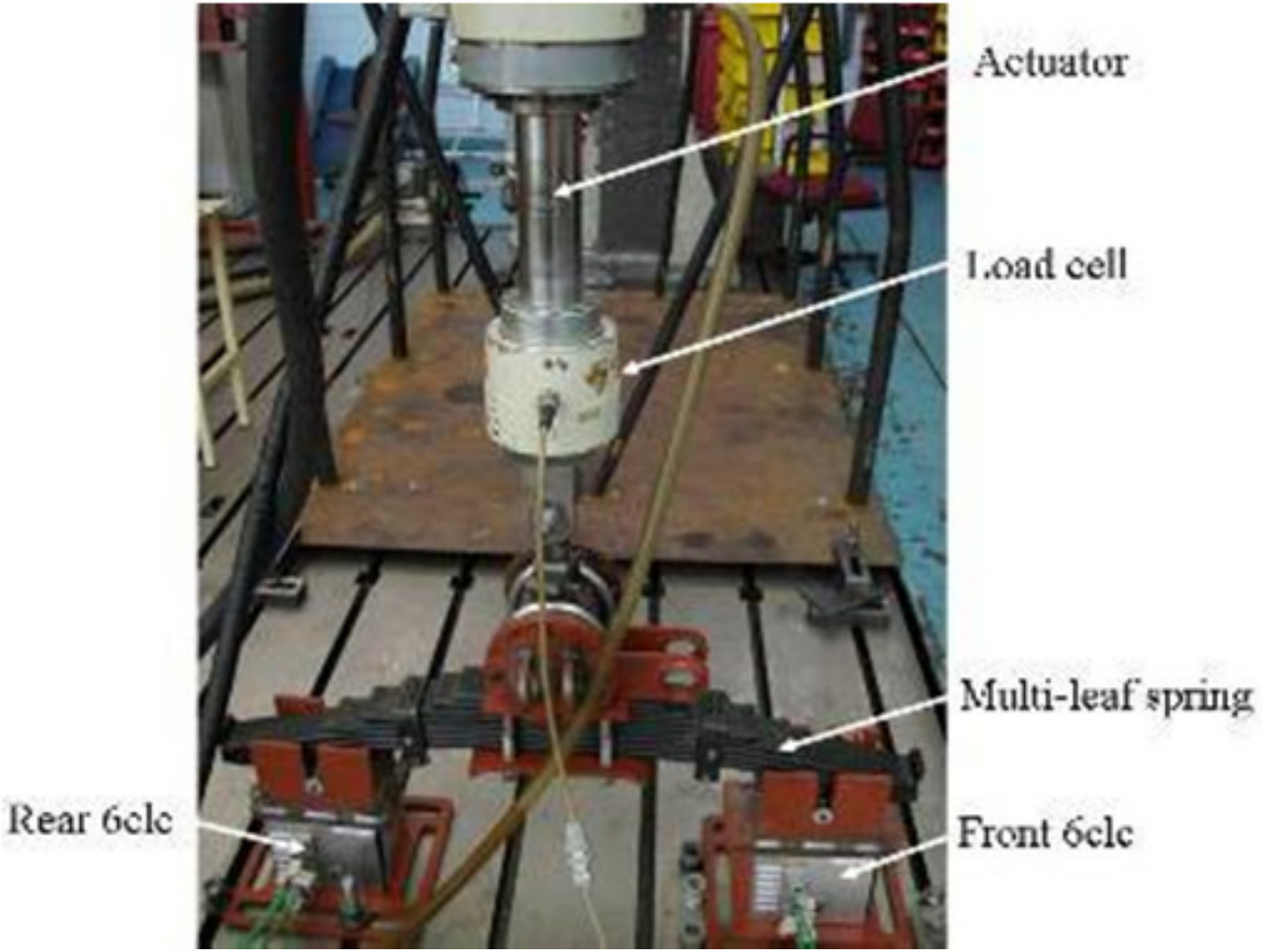


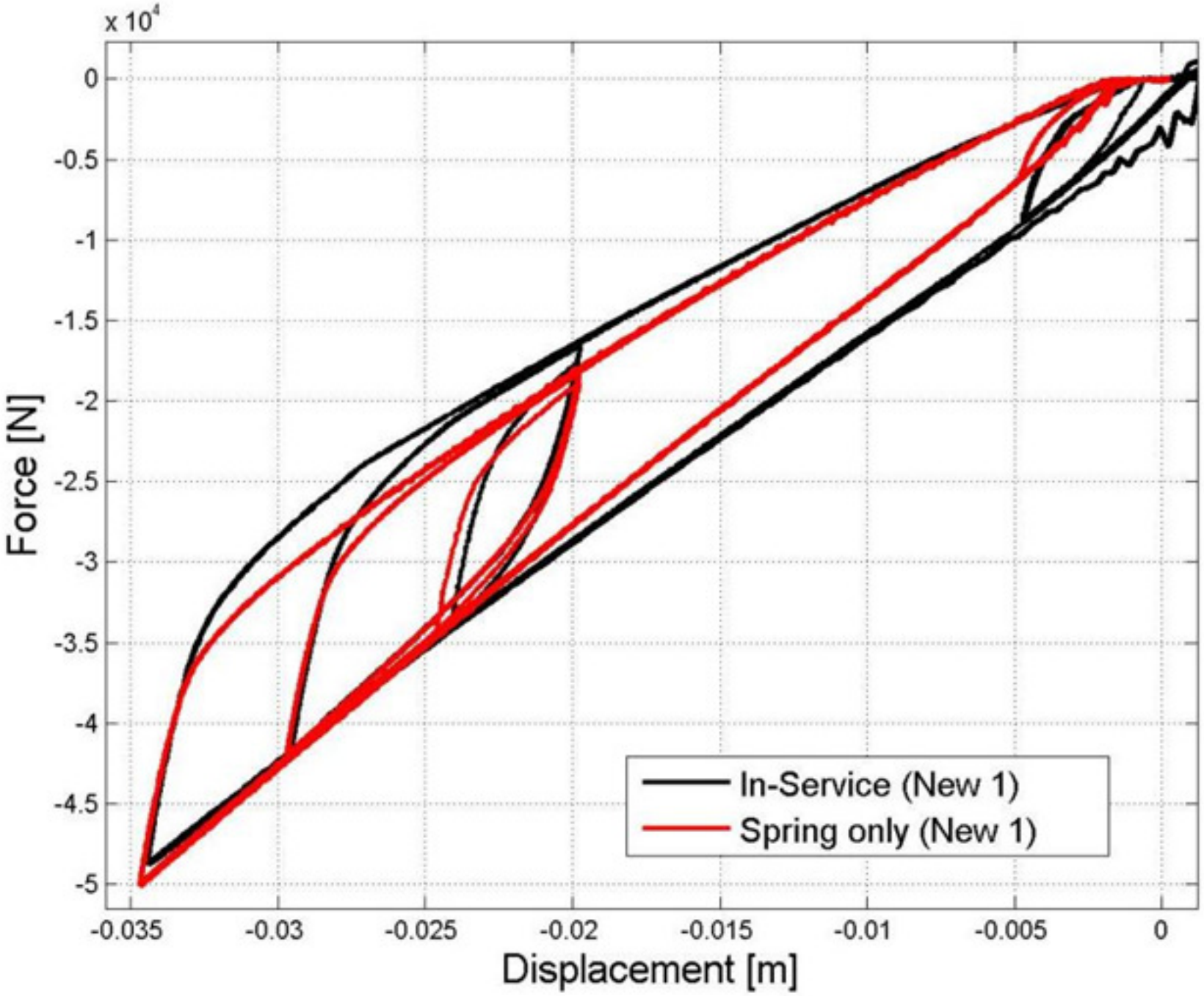
Experimental characteristics

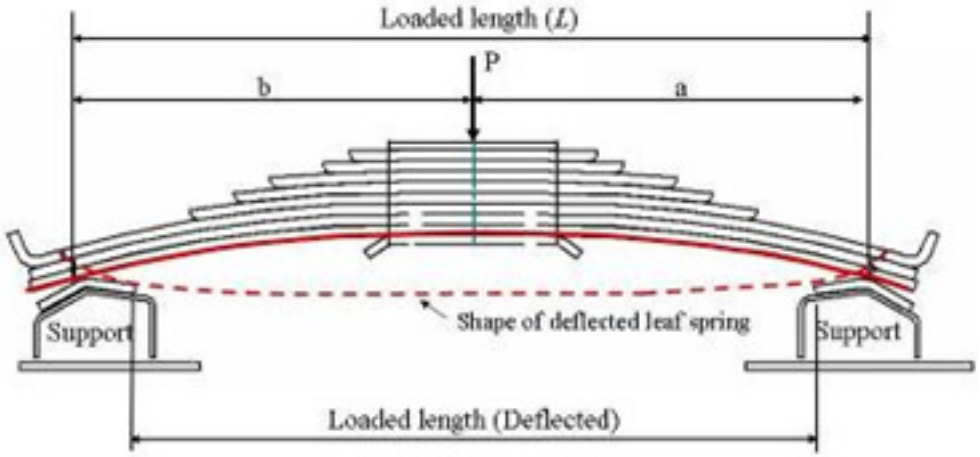


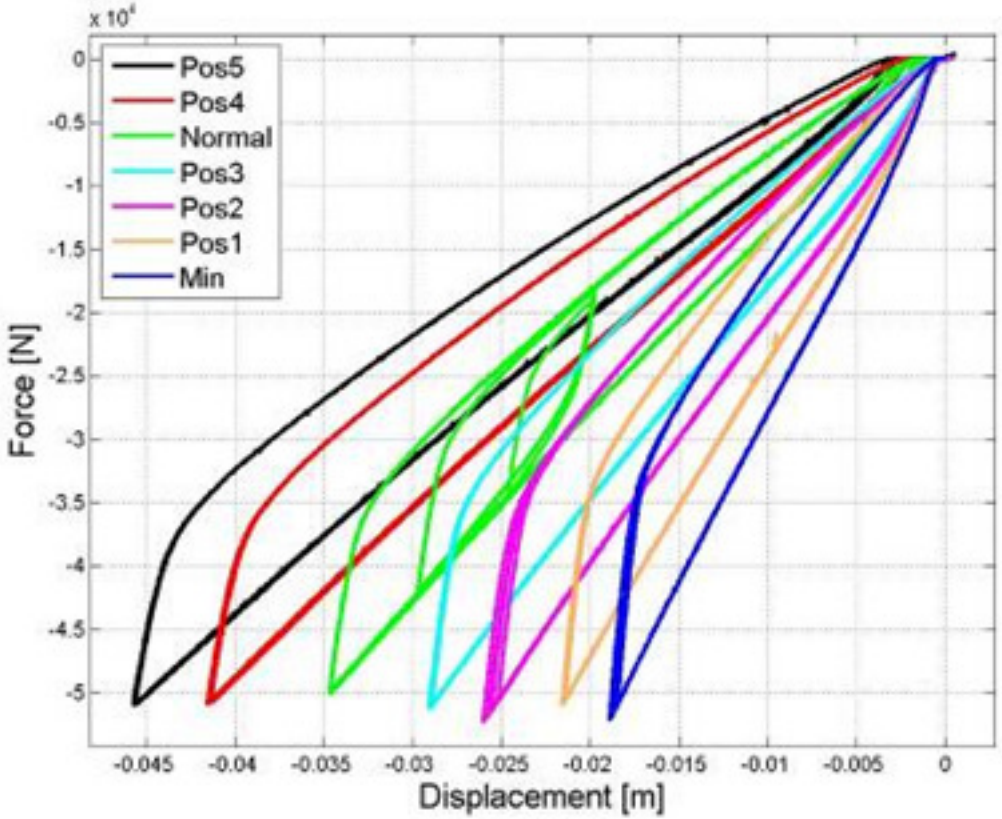


Spring only setup

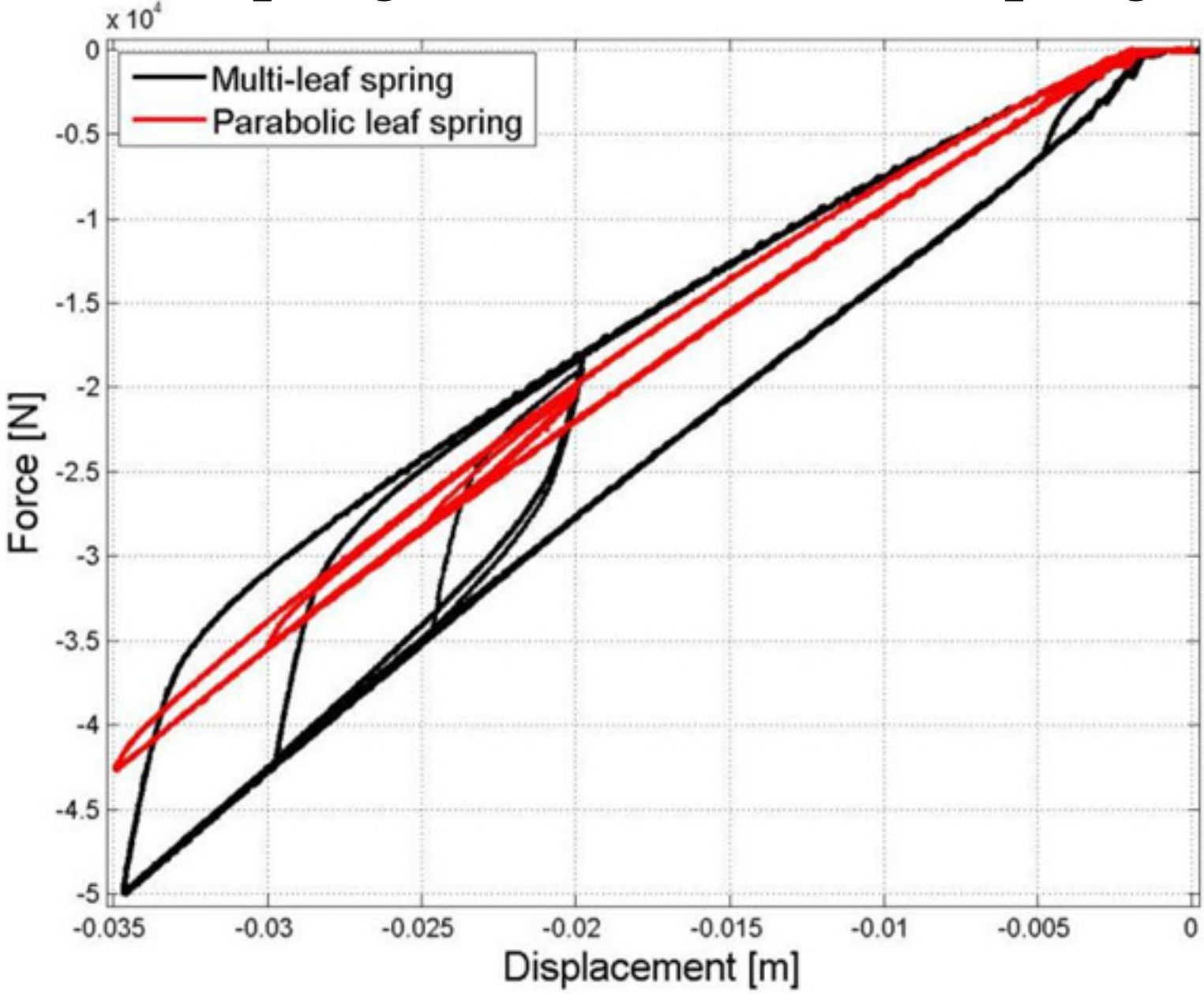


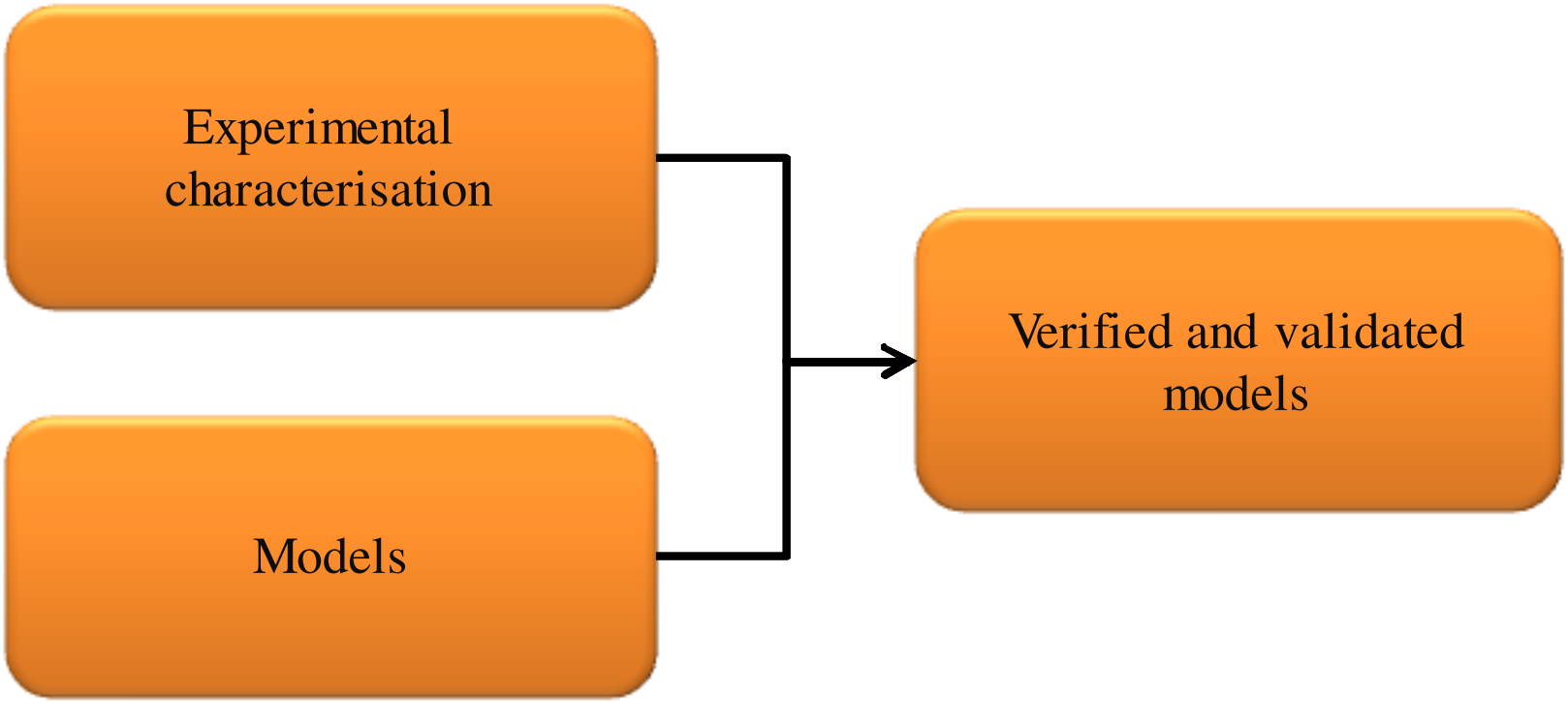

x 10^4
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
Force [N]
-0.035
-0.03
-0.025
-0.02
-0.015
-0.01
-0.005
0
Displacement [m]
In-Service (New 1)
Spring only (New 1)


Loaded length (L)
P
b
a
Support
Shape of deflected leaf spring
Support
Loaded length (Deflected)

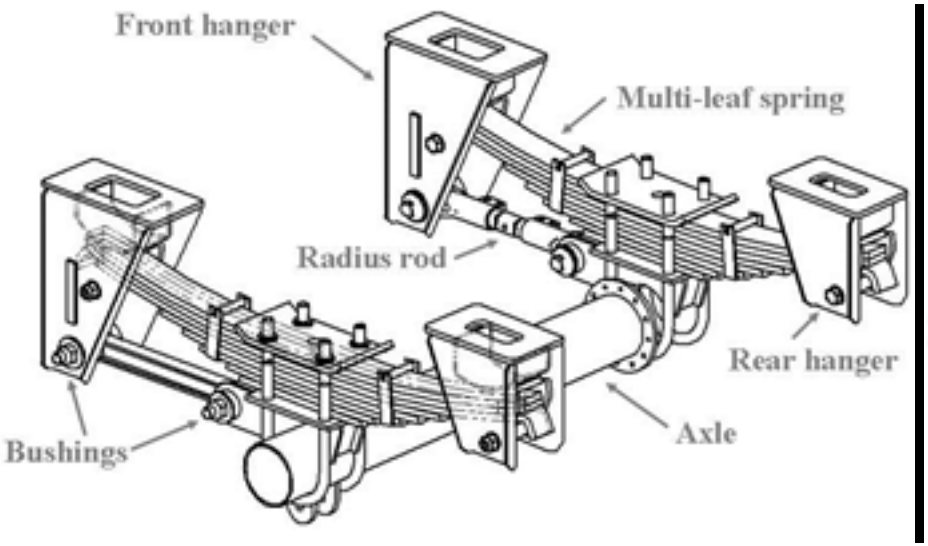

x 10^4
Pos5
Pos4
Normal
Pos3
Pos2
Pos1
Min
Force [N]
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-0.045
-0.04
-0.035
-0.03
-0.025
-0.02
-0.015
-0.01
-0.005
0
Displacement [m]

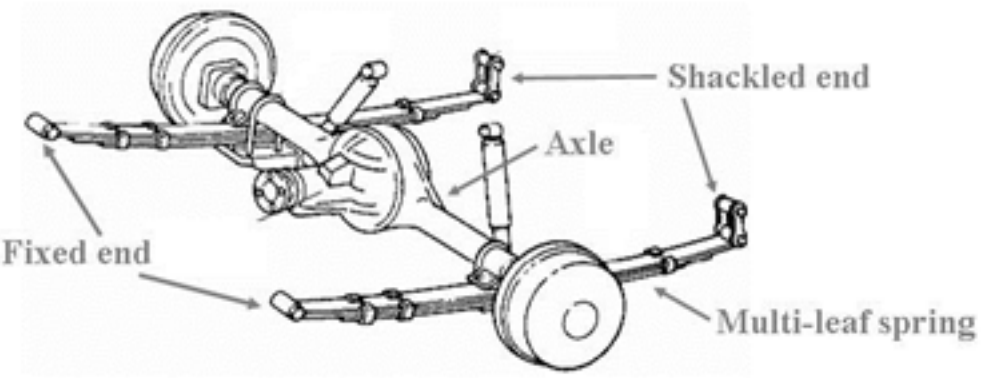
Multi-leaf spring vs. Parabolic leaf spring

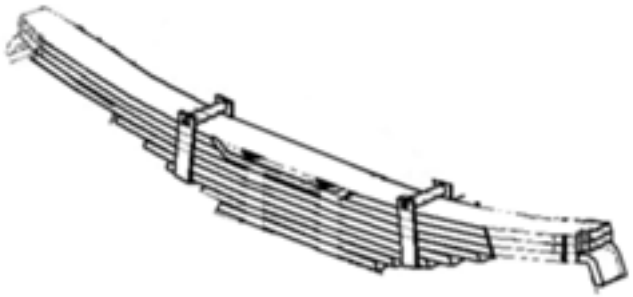



Experimental characterisation
Models
Verified and validated models

Leaf spring models

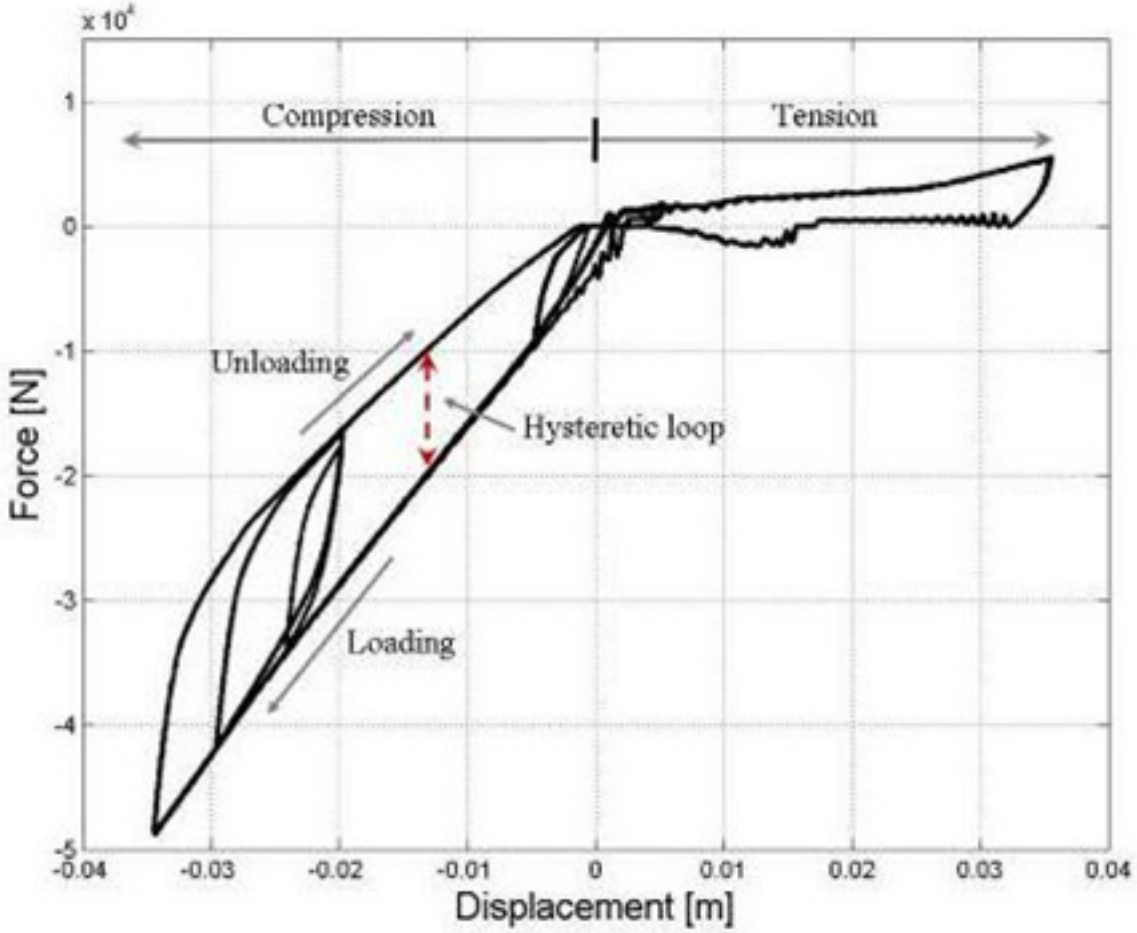


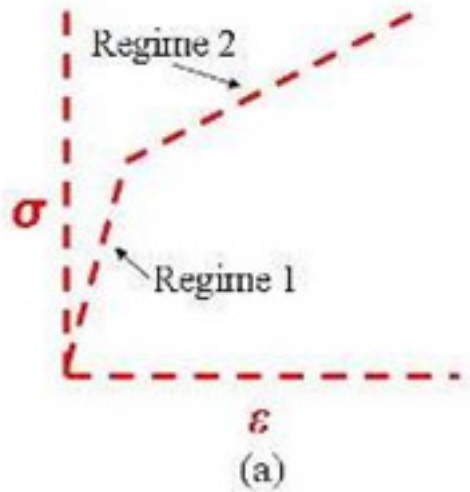


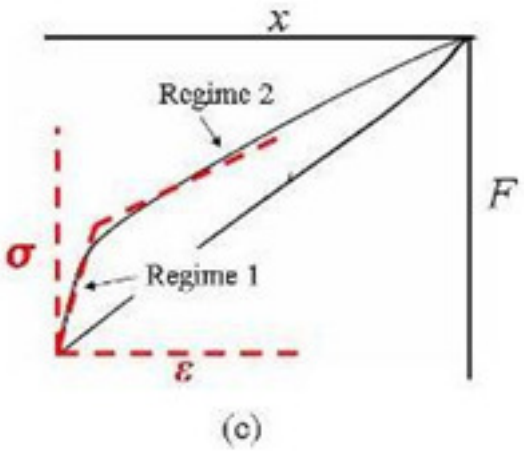


- Beam theory
- Analytical/empirical models
- Equivalent models
- Discrete methods (or Finite segment method)
- Finite element methods
- **Neural network models**
- Lumped mass spring models
- Graphical techniques
- Kinematic models

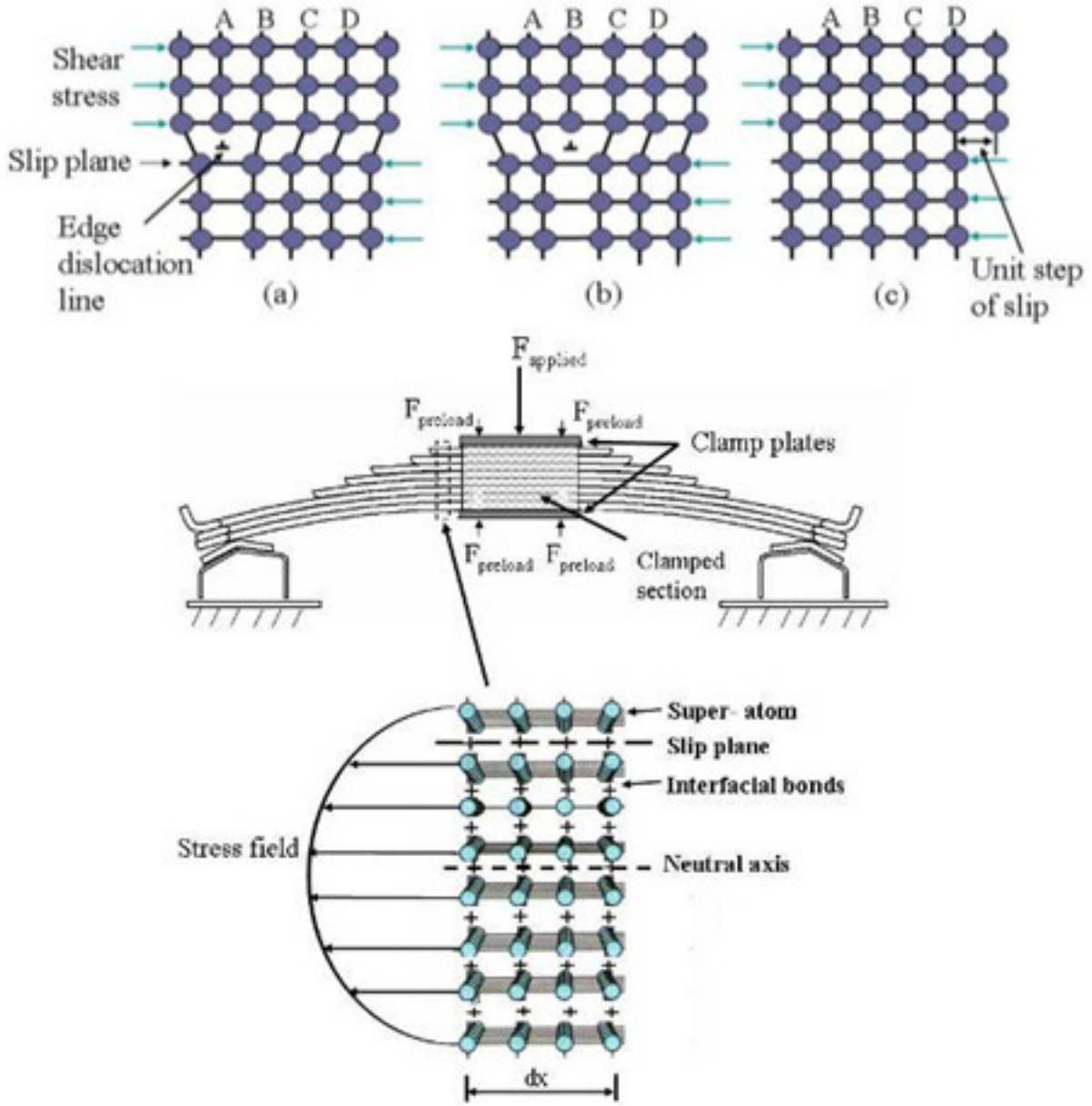
Elasto-plastic leaf spring model

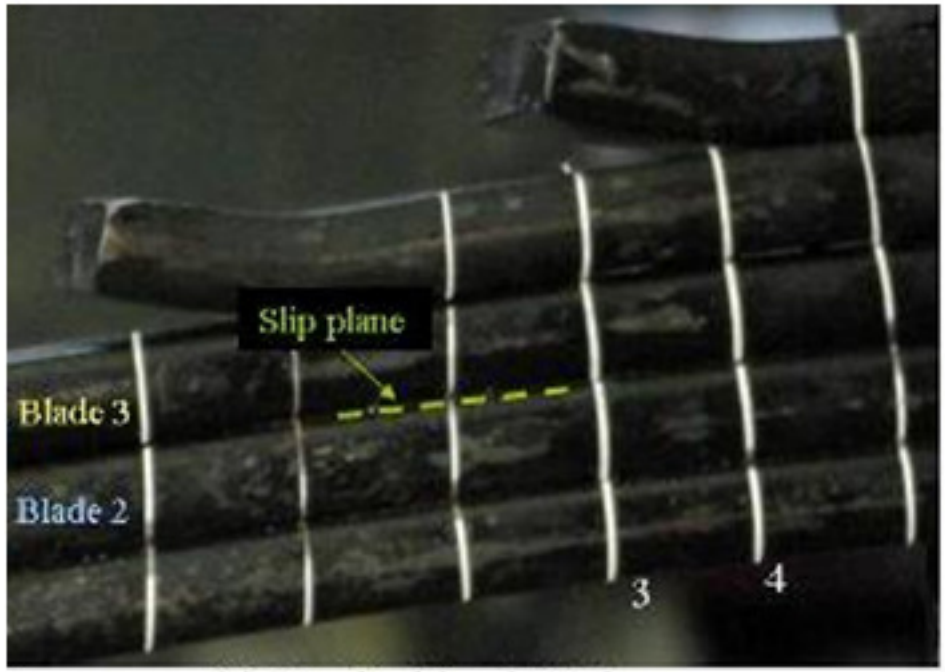




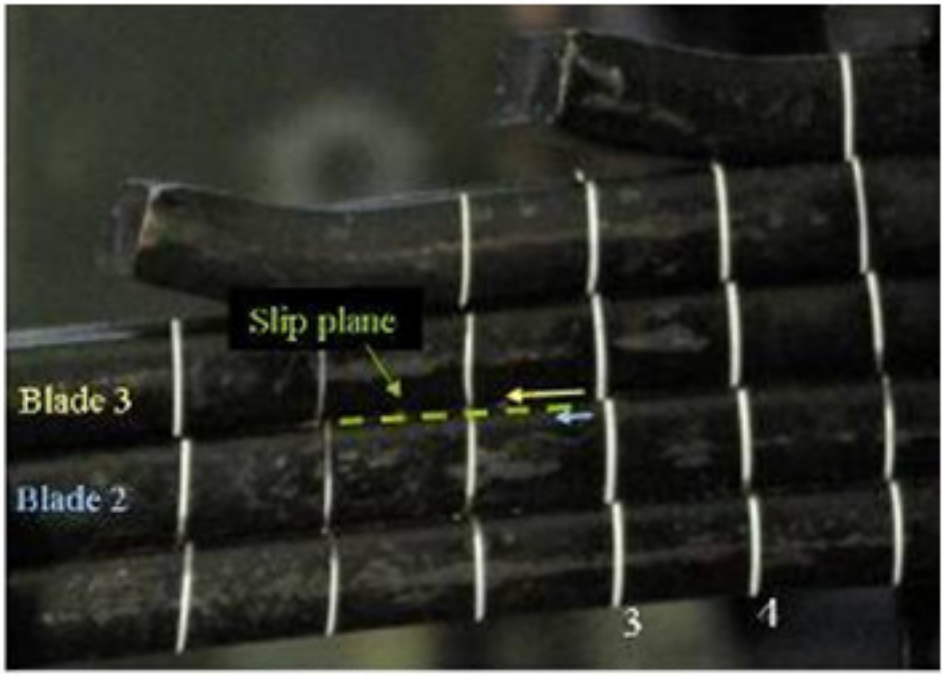


Mechanisms: materials vs. multi-leaf springs





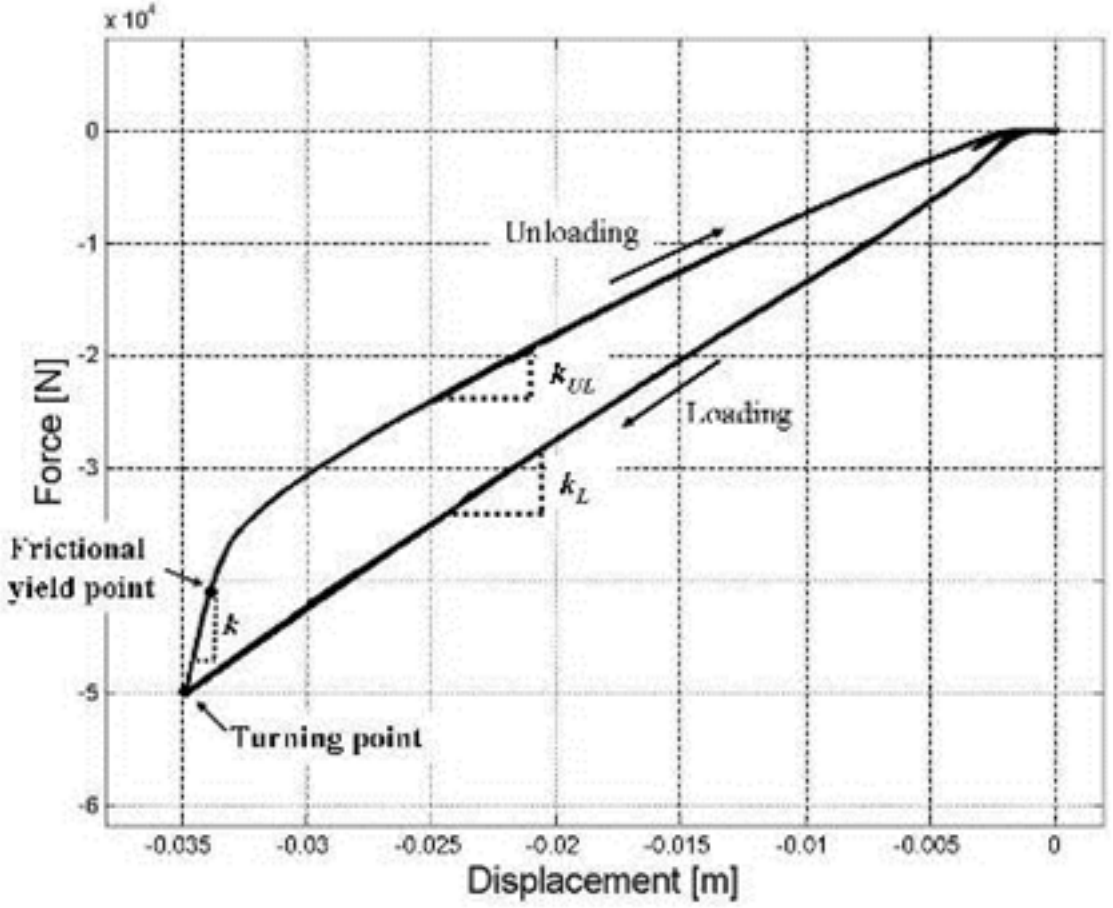
(a) Vertical load 677kg



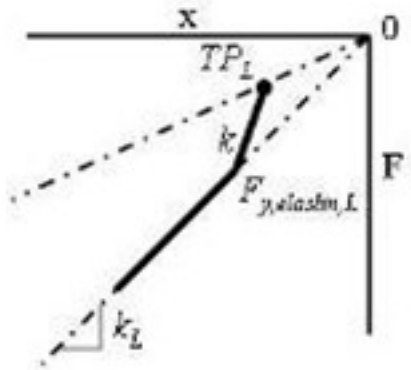
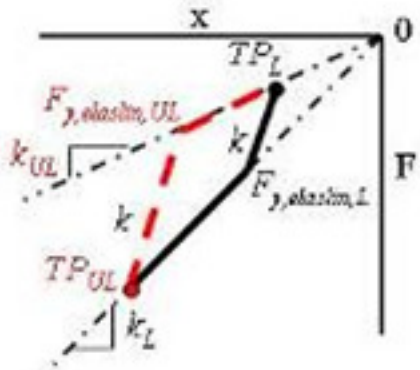
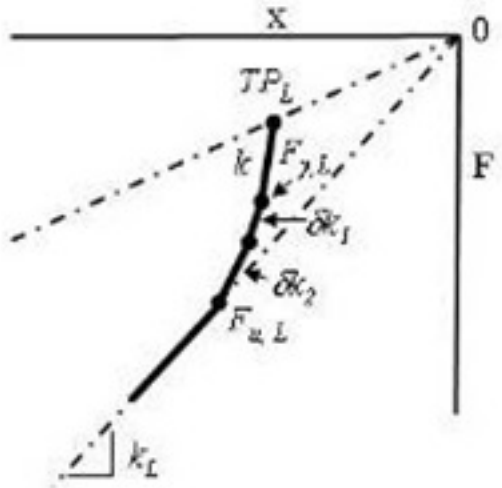
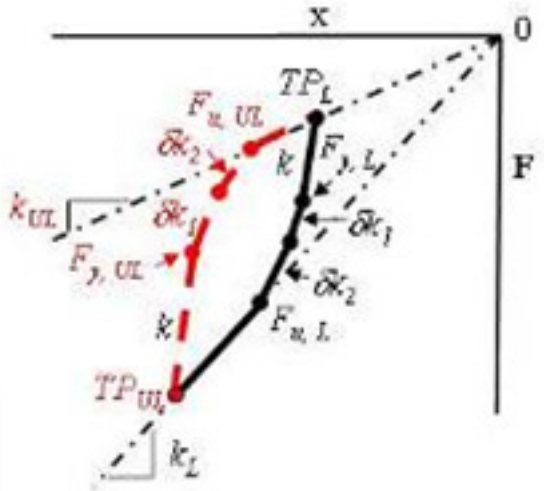
(b) Vertical load 4105kg

Mechanical properties

k - stiffness of the solid beam,
k_L - stiffness of the layered beam during loading,
k_{UL} - stiffness of the layered beam during unloading,
f_y - yield fraction



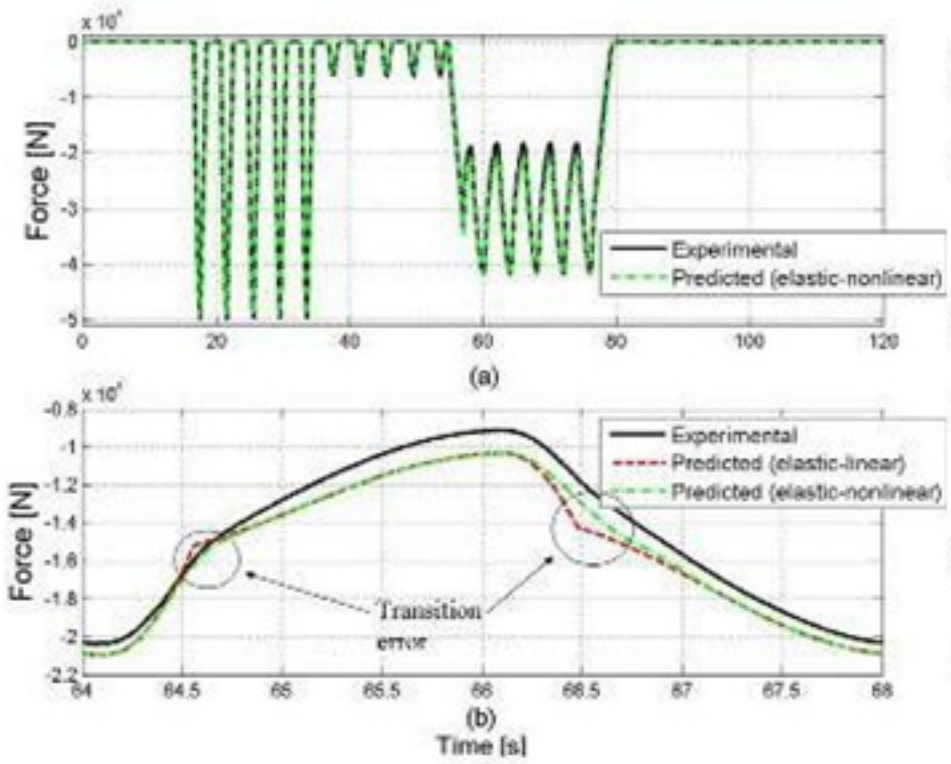
EPLS model formulation

Model	Force-displacement response (Monotonic loading)	Force-displacement response (Monotonic-bidirectional loading)
(a) Elastic-linear		
(b) Elastic-nonlinear		

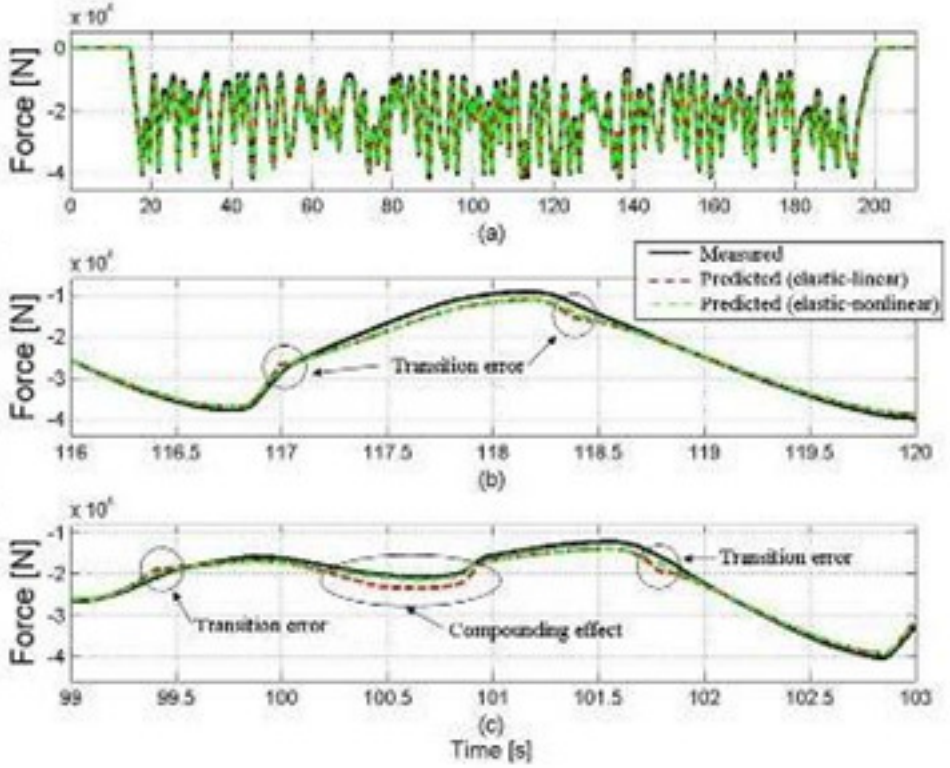
Advantages & Disadvantages

Validation results

Sinusoidal input



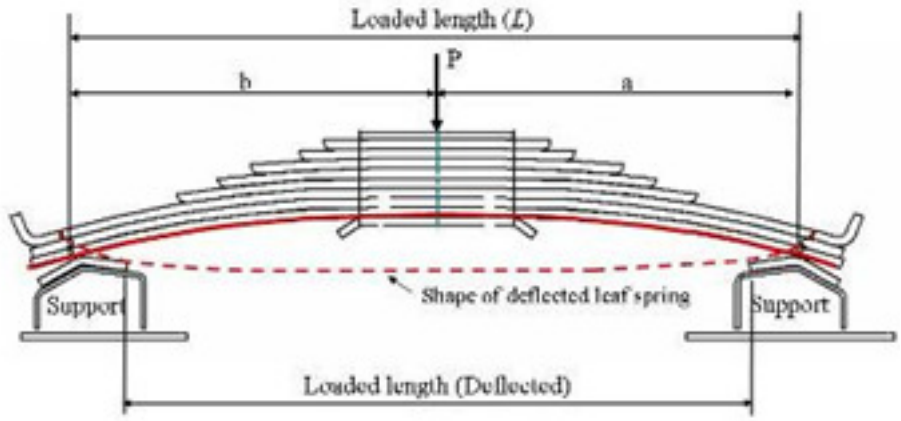
Random input



EPLS model conclusions

- Parameterisation
- Accurate
- Applied to parabolic leaf spring
- Application to simply supported leaf spring

Method to account for loaded length changes



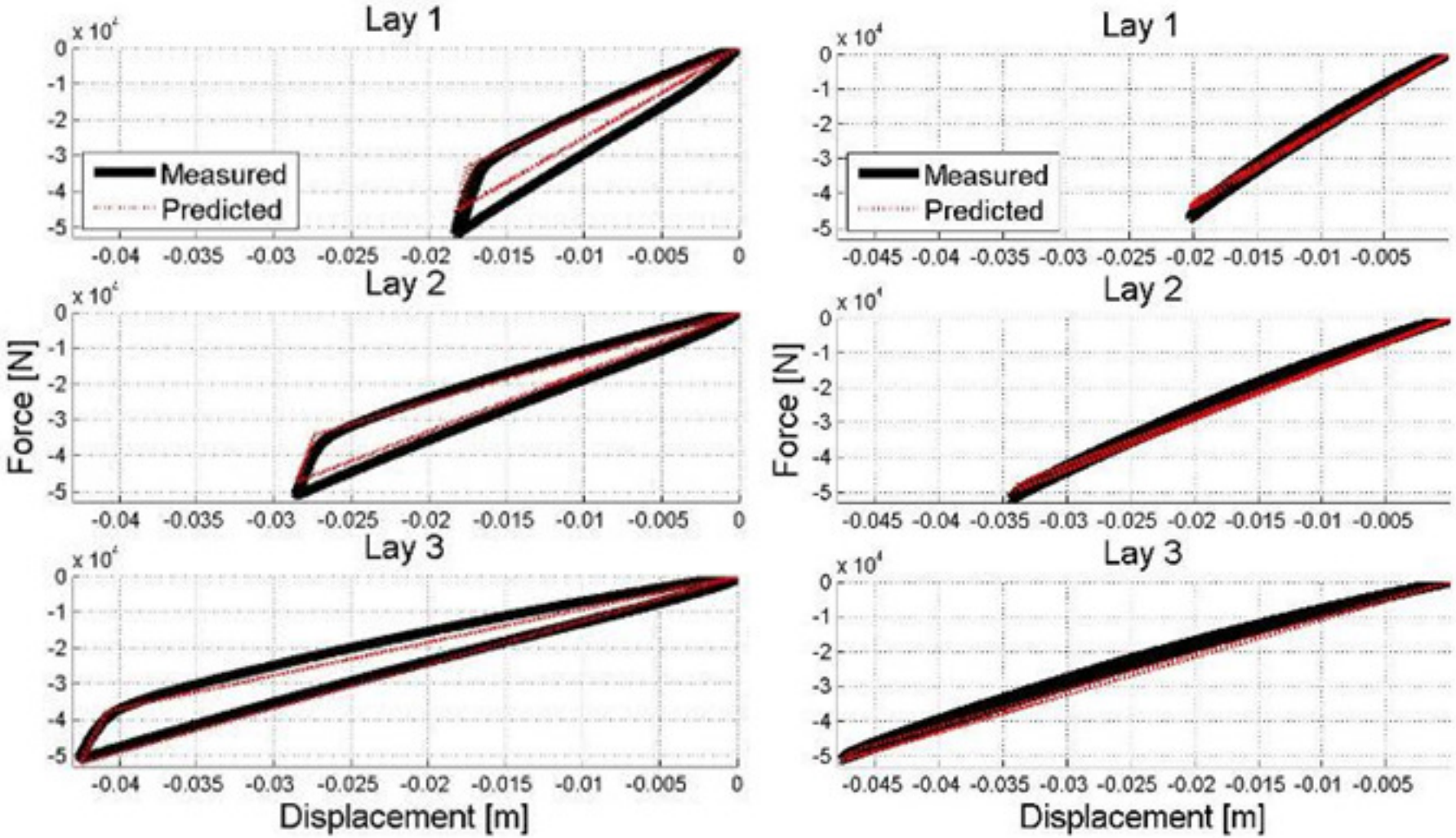
$$\upsilon = -\frac{Pbx}{6LEI}(L^2 - b^2 - x^2) \qquad (0 \le x \le a)$$

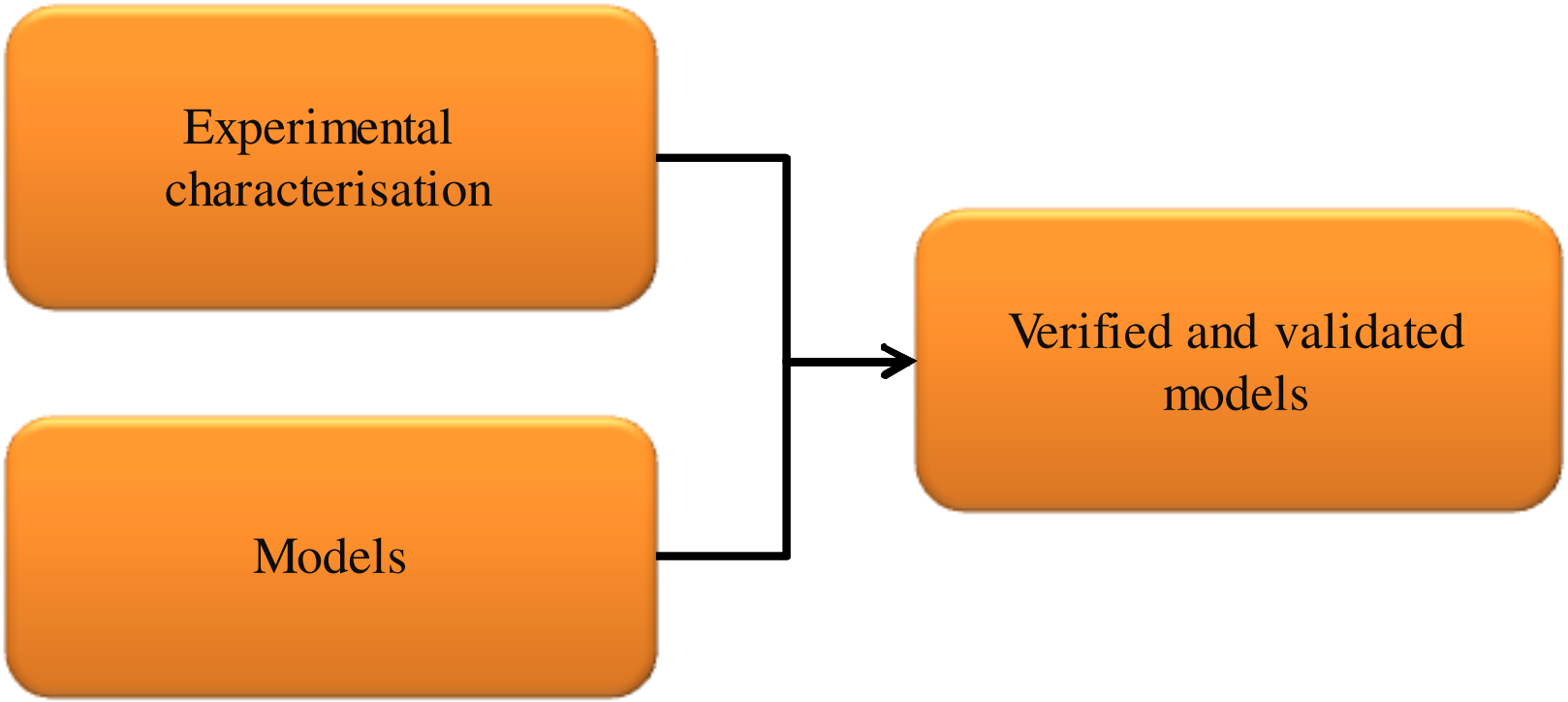
It can easily be shown that

$$k_2 = k_1 \frac{b_1 a_1 L_2 (b_1^2 + a_1^2 - L_1^2)}{b_2 a_2 L_1 (b_2^2 + a_2^2 - L_2^2)}$$

Multi-leaf spring

Parabolic leaf spring




Experimental characterisation
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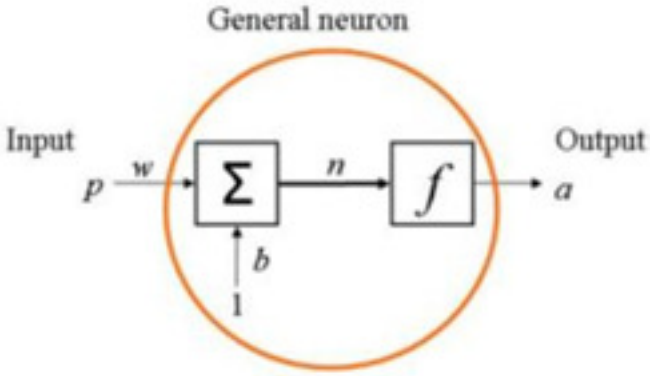
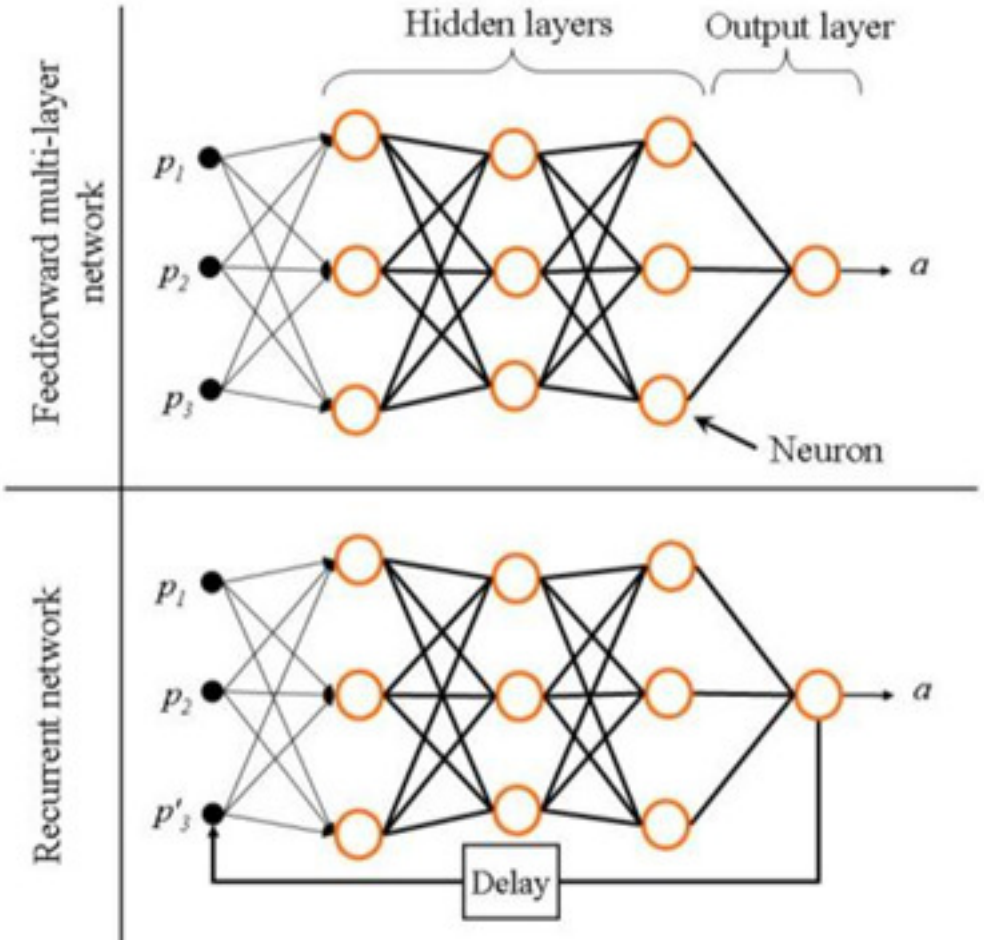
Neural networks

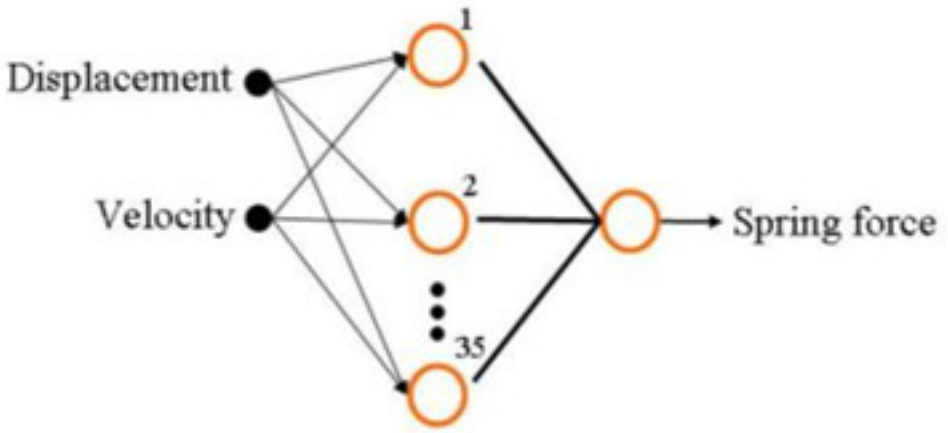
Artificial neural networks



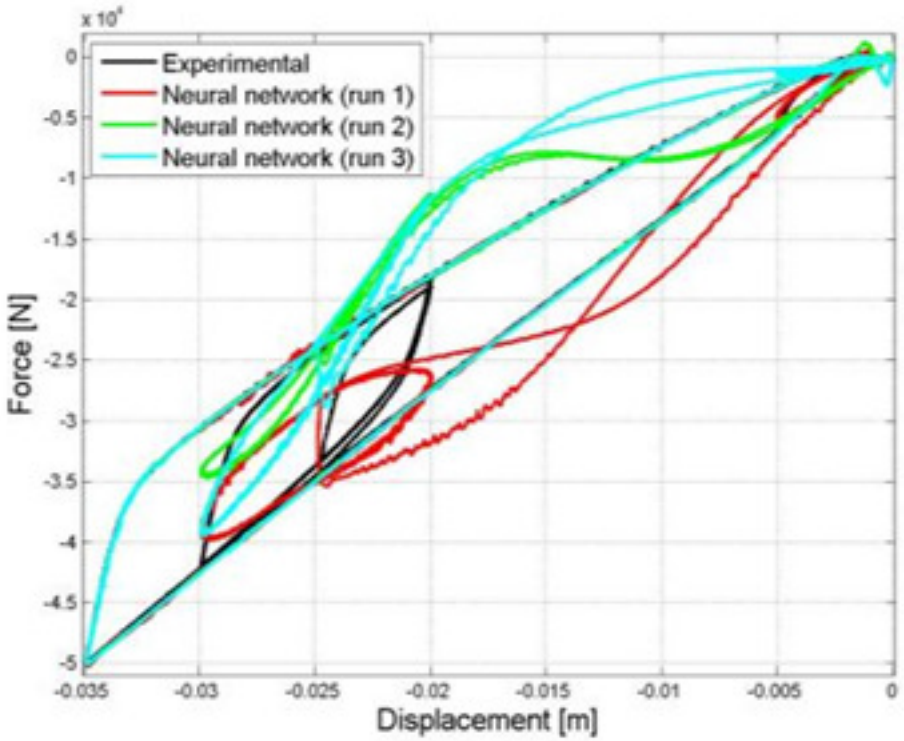


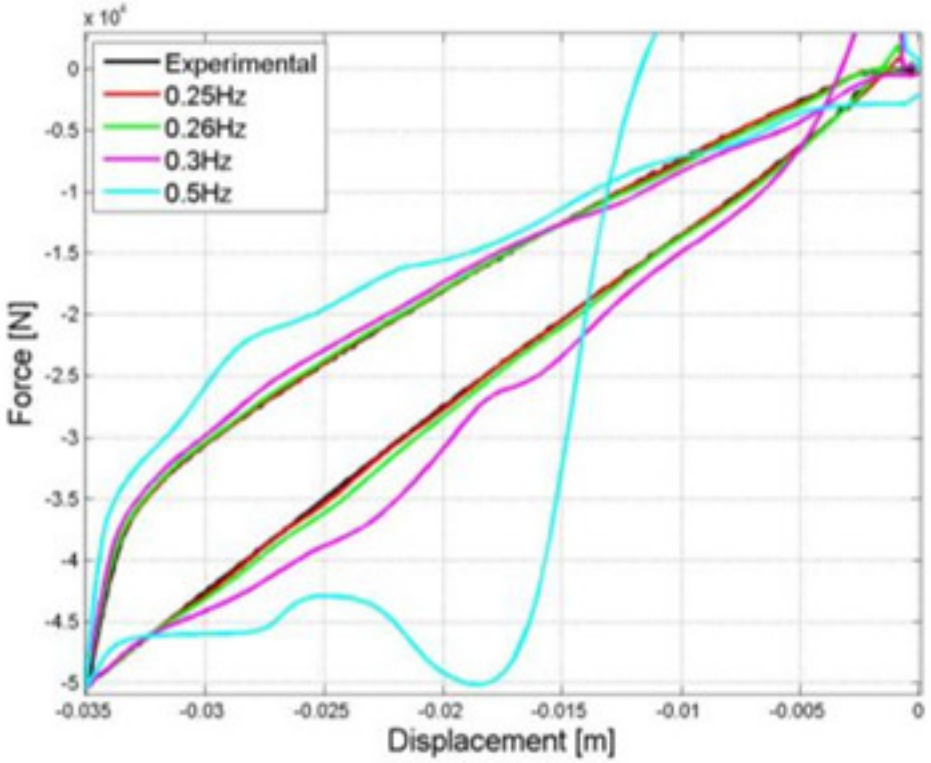
Creating ANN

- Find the ***relevant inputs***
- Collect ***data*** necessary for training and testing of the neural network
- ***Training*** of the network
- Find appropriate ***complexity*** of the network (i.e. number of layers, number of neurons)
- Assess ***generalization*** ability of neural network

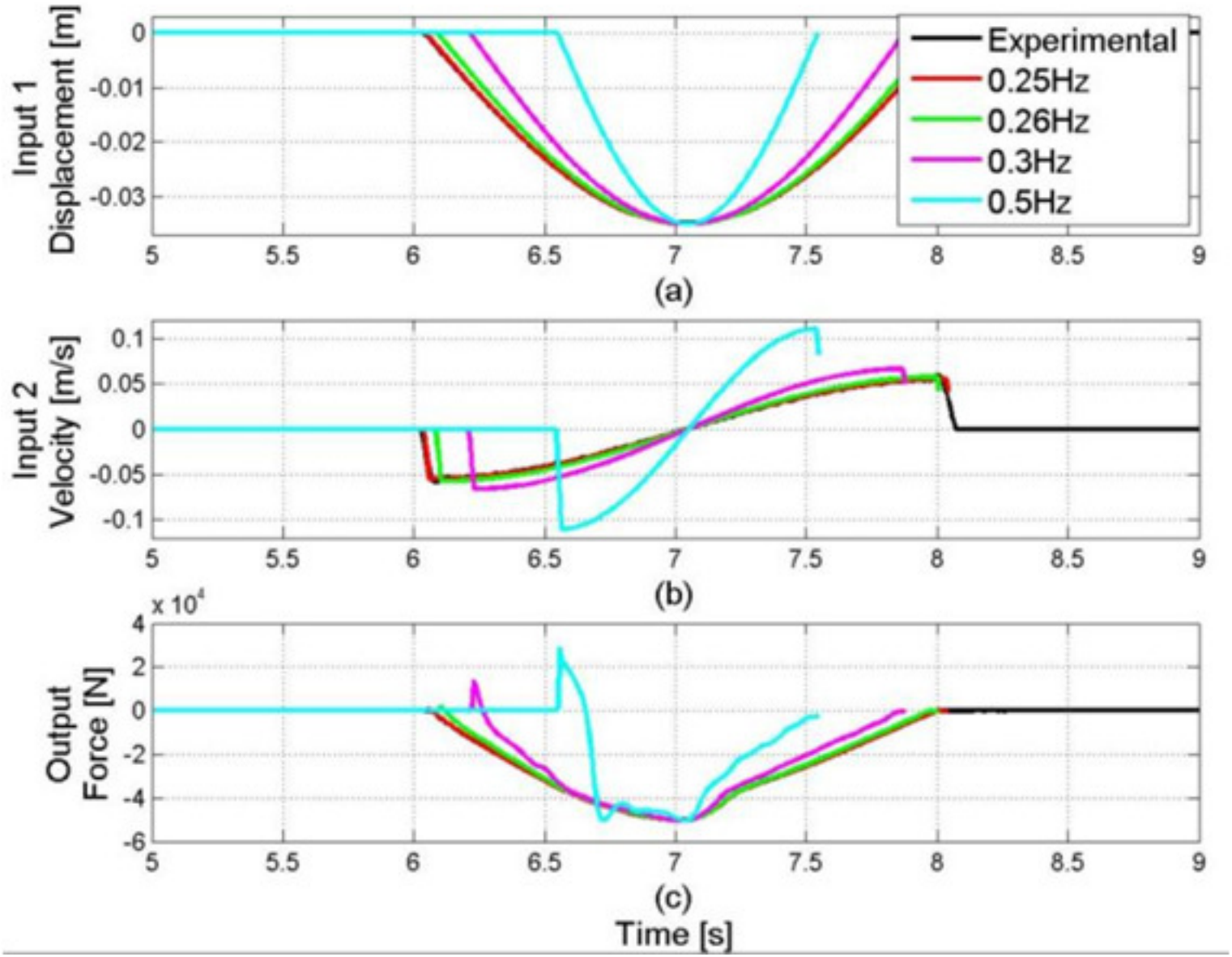


Ability to generalise

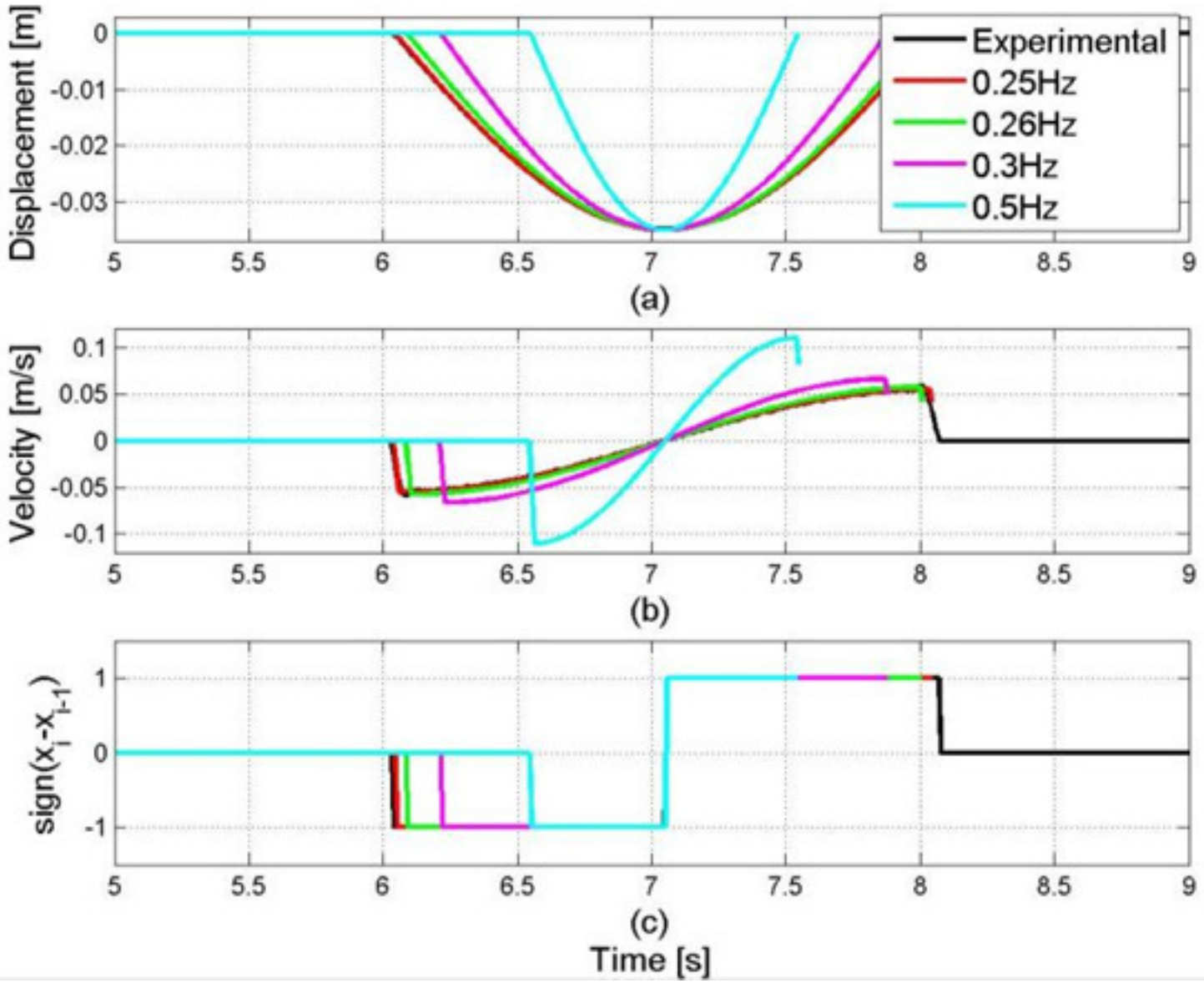




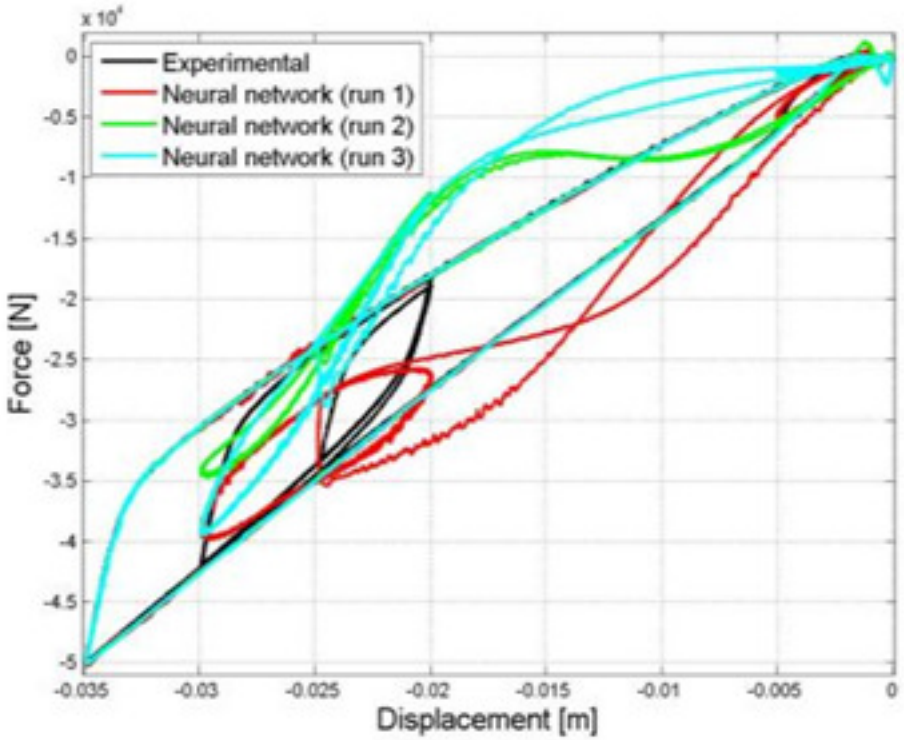
Importance of inputs

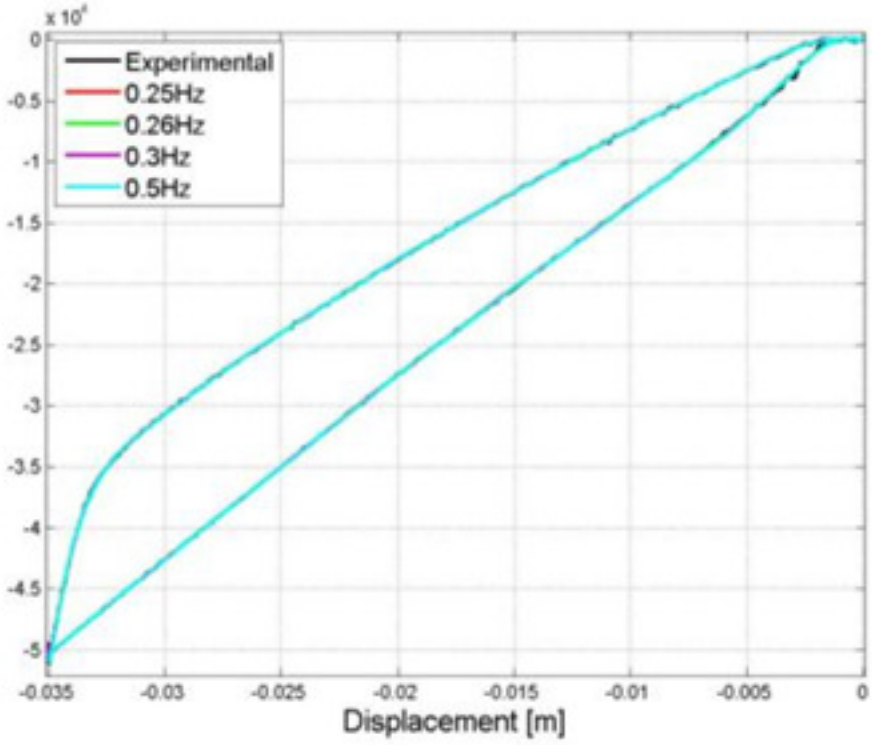


Importance of inputs



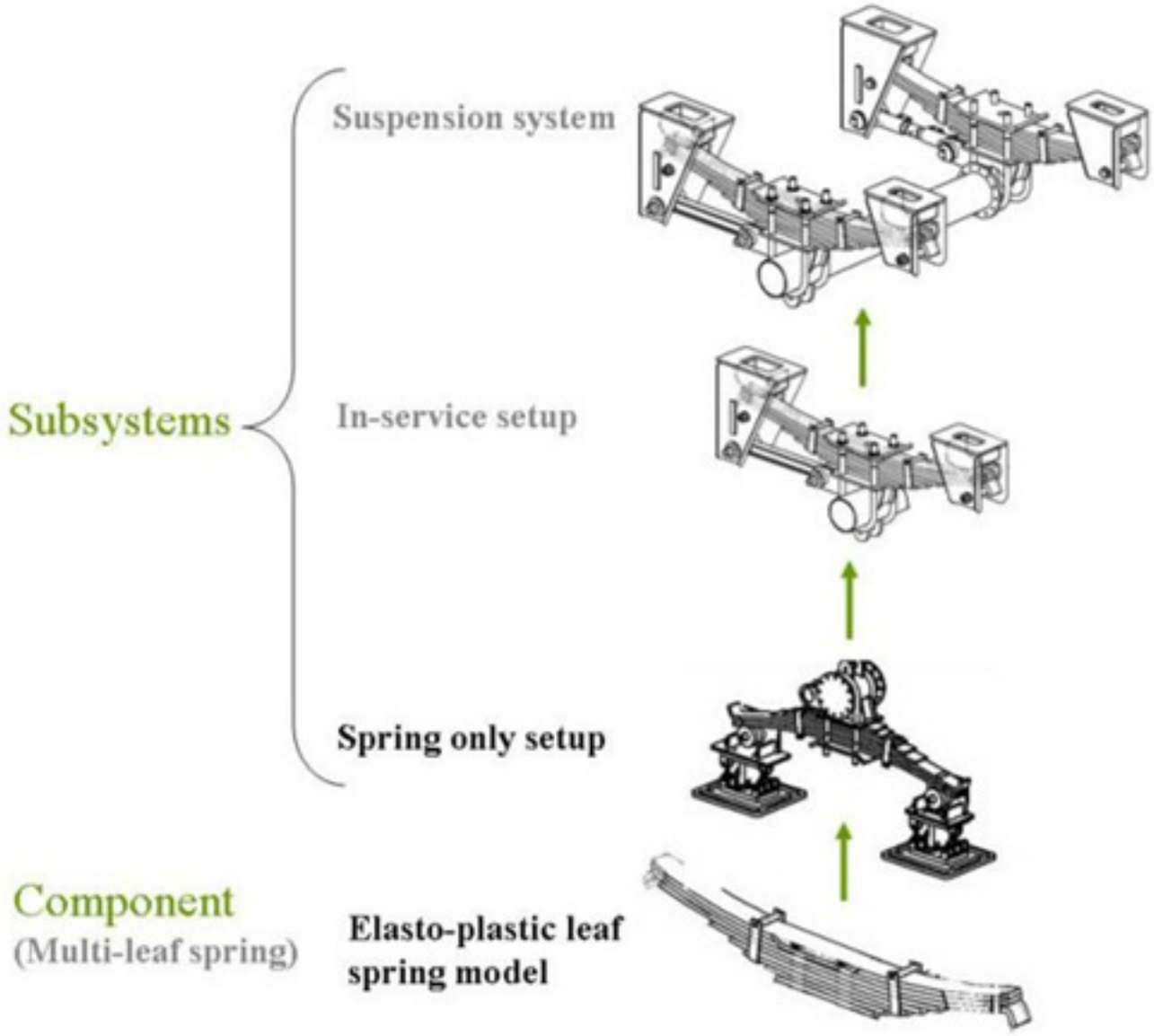
Effect of inputs on generalisation

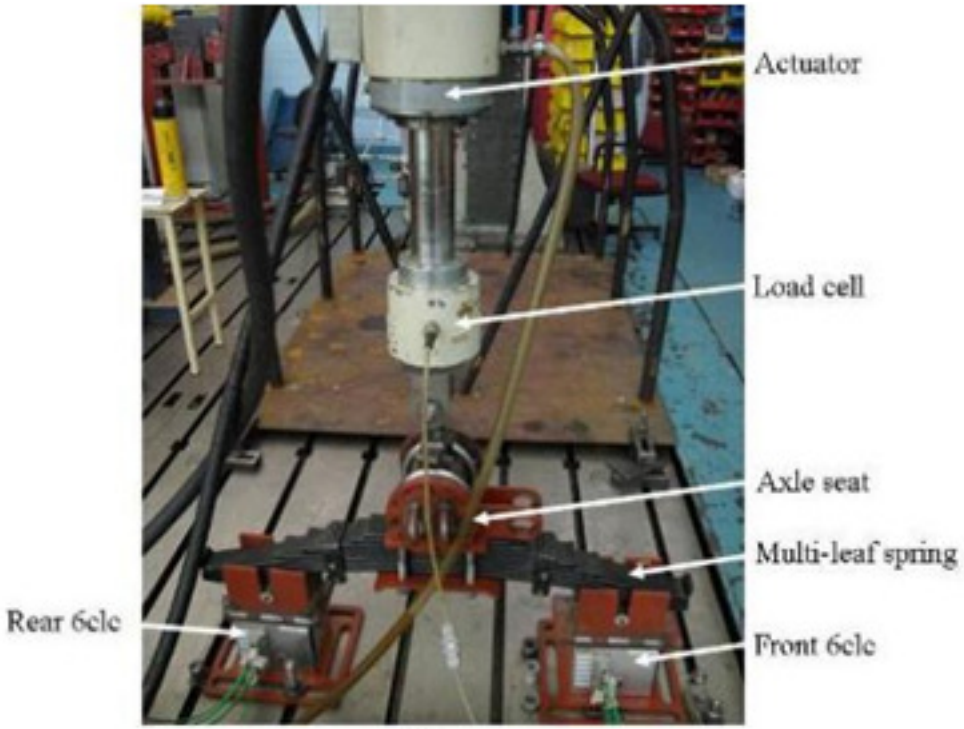


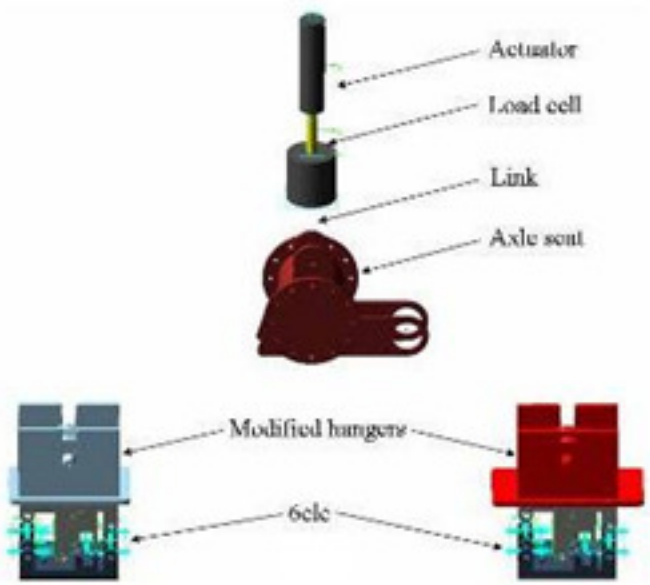


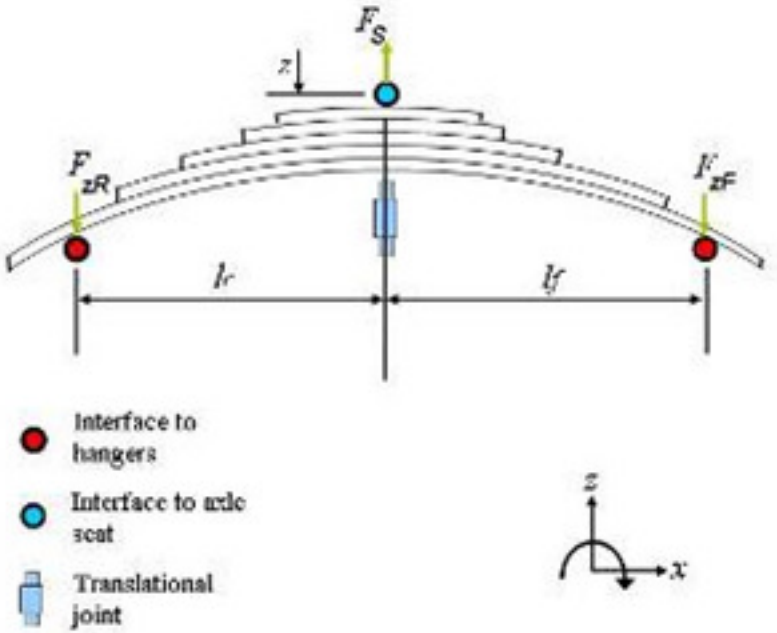
"Intelligence"

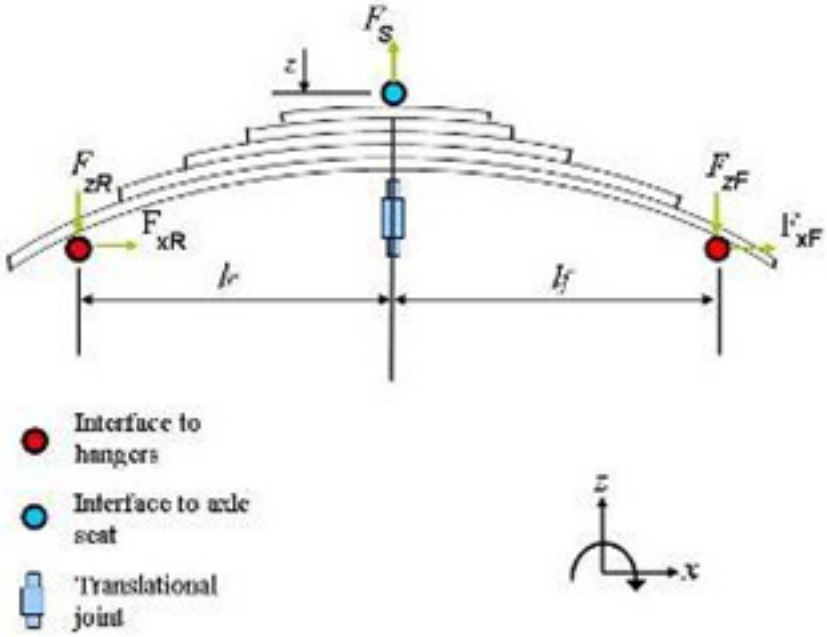
Multi-leaf spring suspension system model

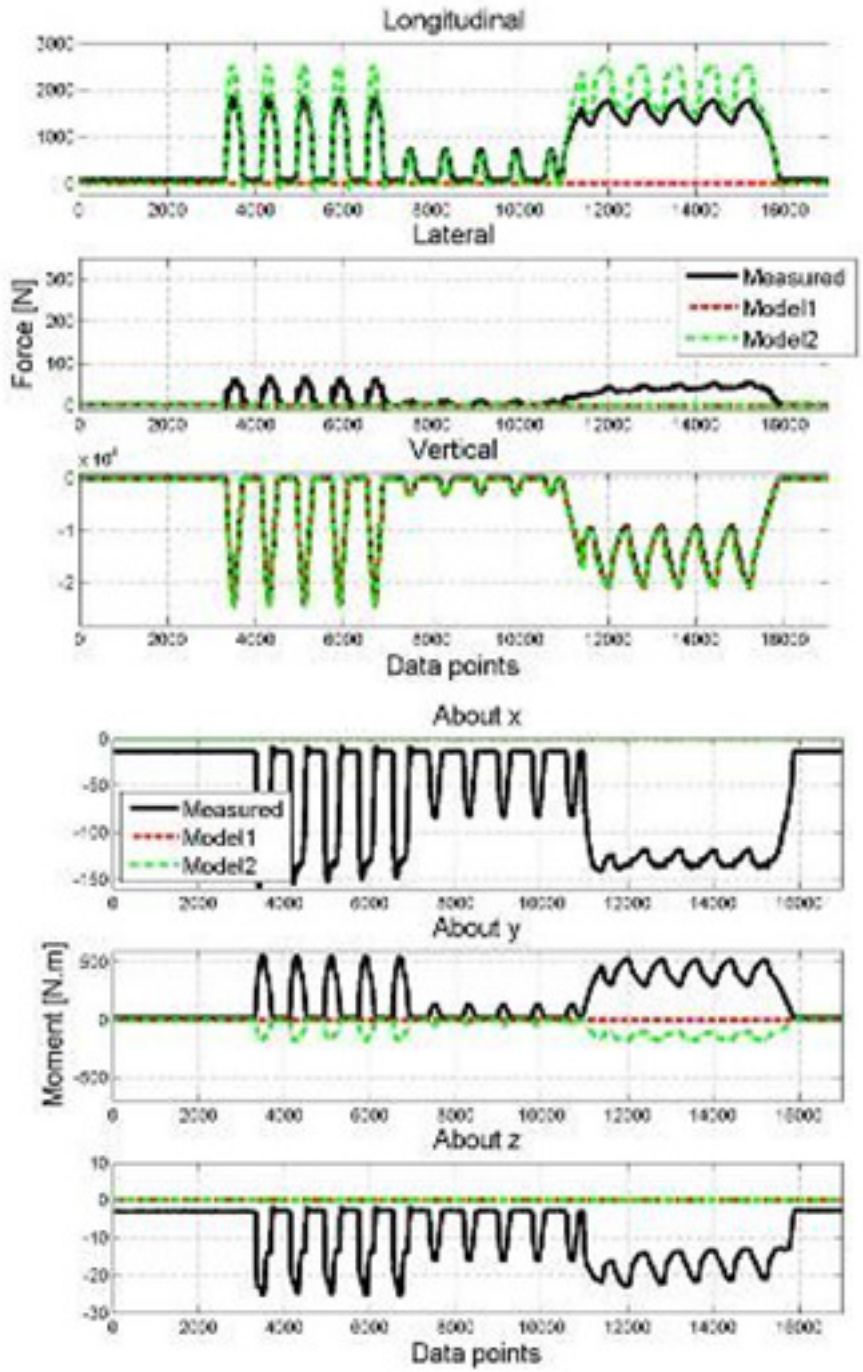


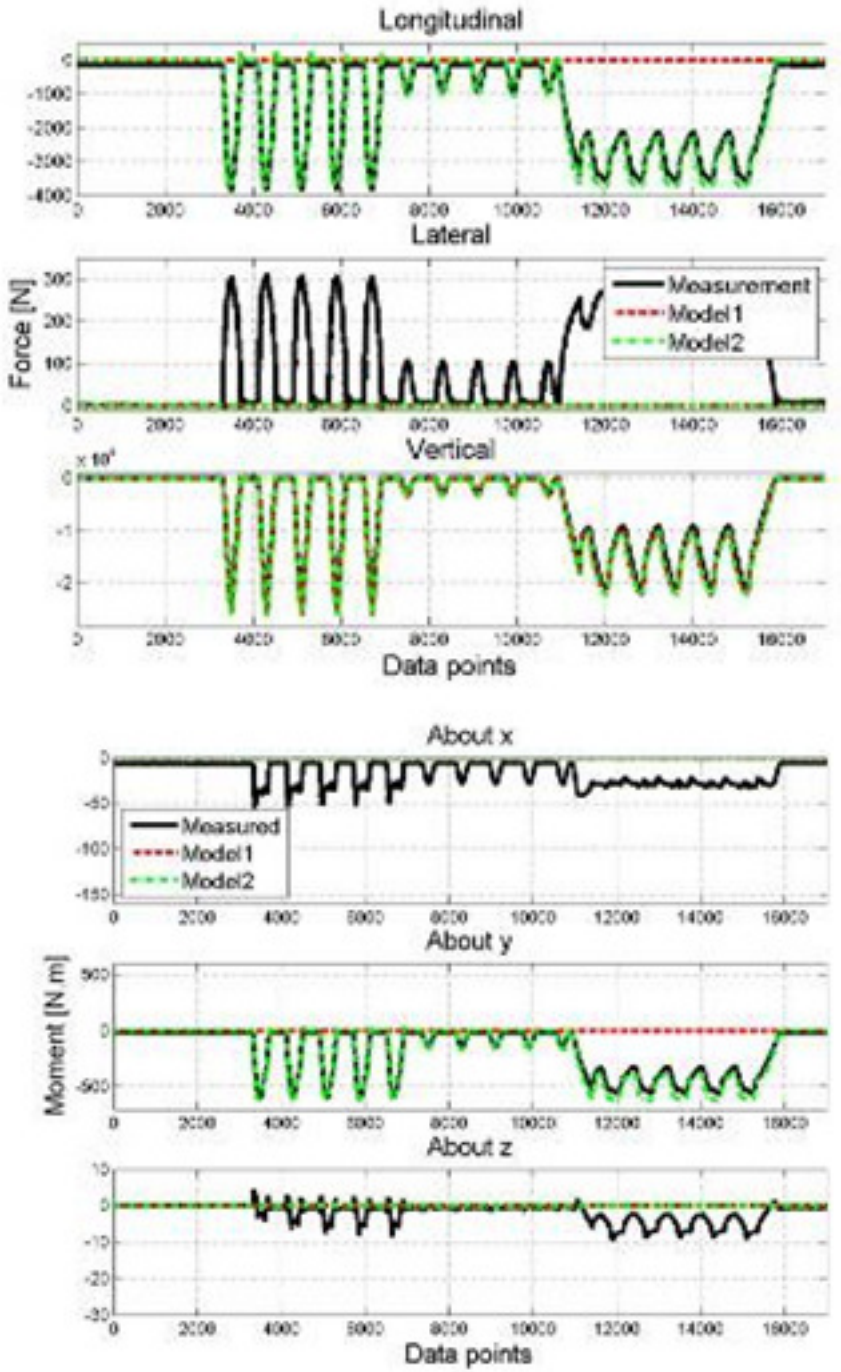

Actuator
Load cell
Axle seat
Multi-leaf spring
Rear 6clc
Front 6clc


Actuator
Load cell
Link
Axle seat
Modified hangers
6clc

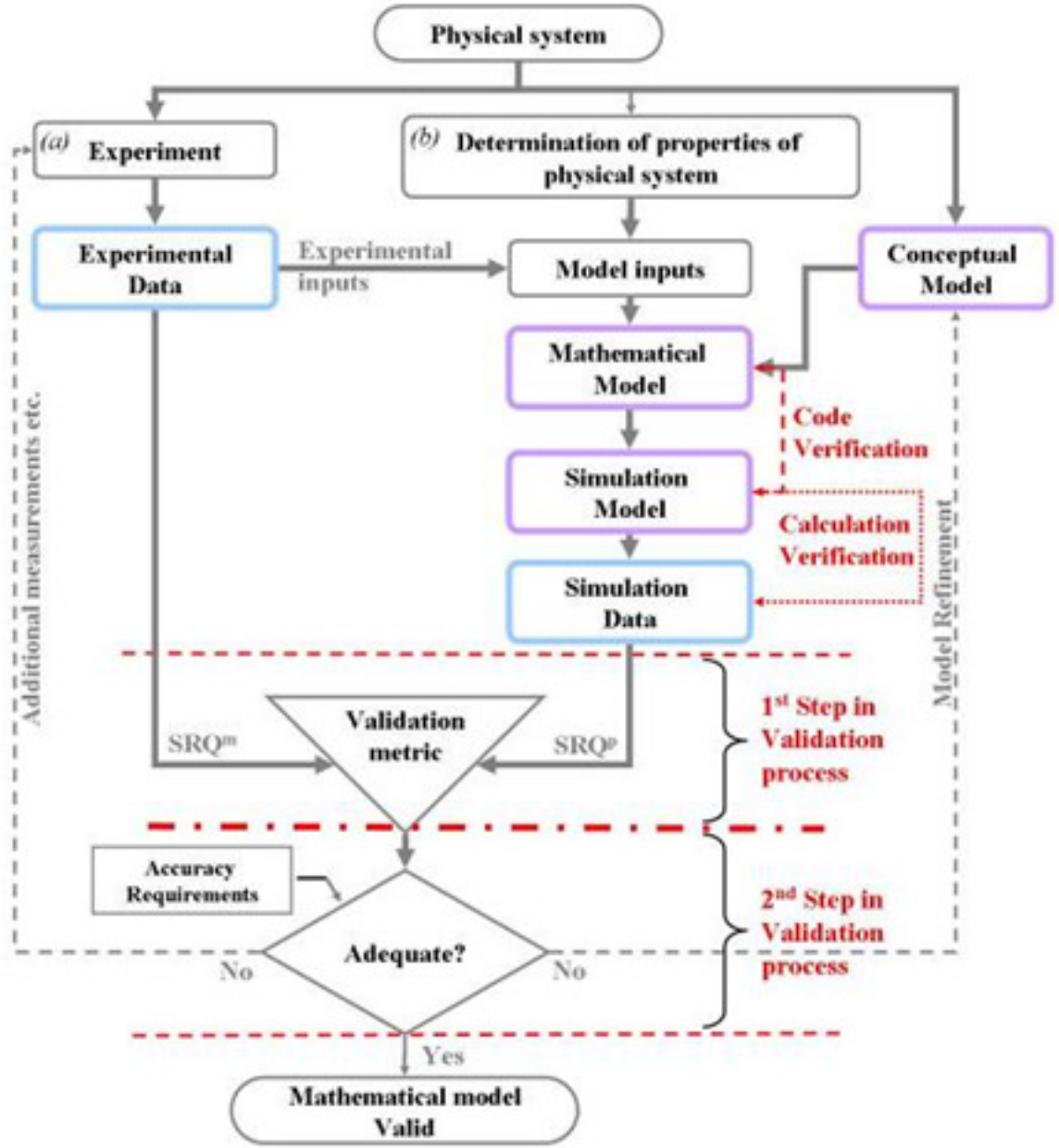

F_S
z
F_{zR}
F_{zF}
l_r
l_f
Interface to hangers
Interface to axle seat
Translational joint
z
x


F_S
z
F_{zR}
F_{xR}
F_{zF}
F_{xF}
l_r
l_f
Interface to hangers
Interface to axle seat
Translational joint
z
x


Longitudinal
Lateral
Force [N]
Measured
Model1
Model2
Vertical
Data points
About x
About y
About z
Moment [N.m]

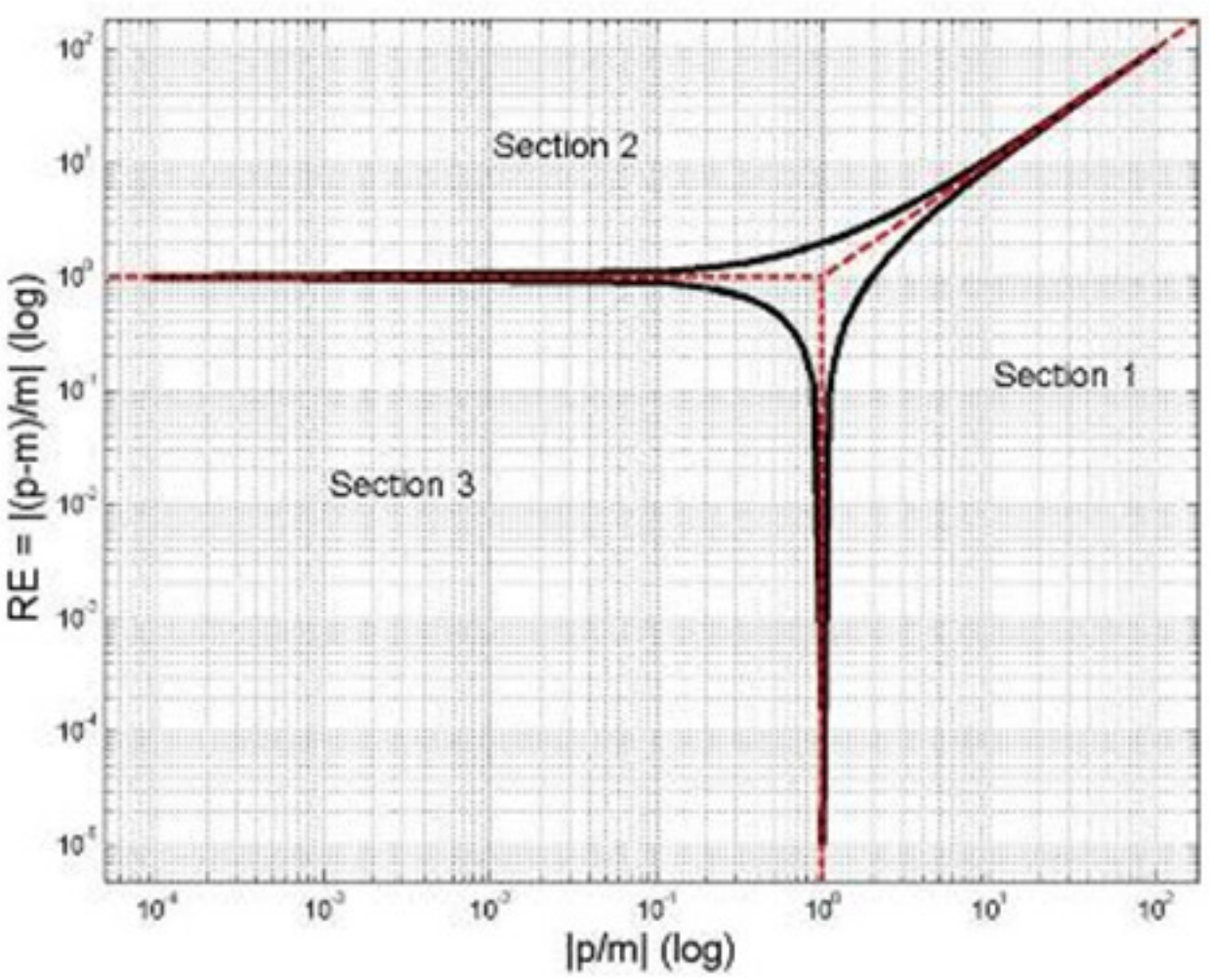

Longitudinal
Lateral
Force [N]
Measurement
Model1
Model2
Vertical
Data points
About x
About y
About z
Moment [N m]

Verification & Validation



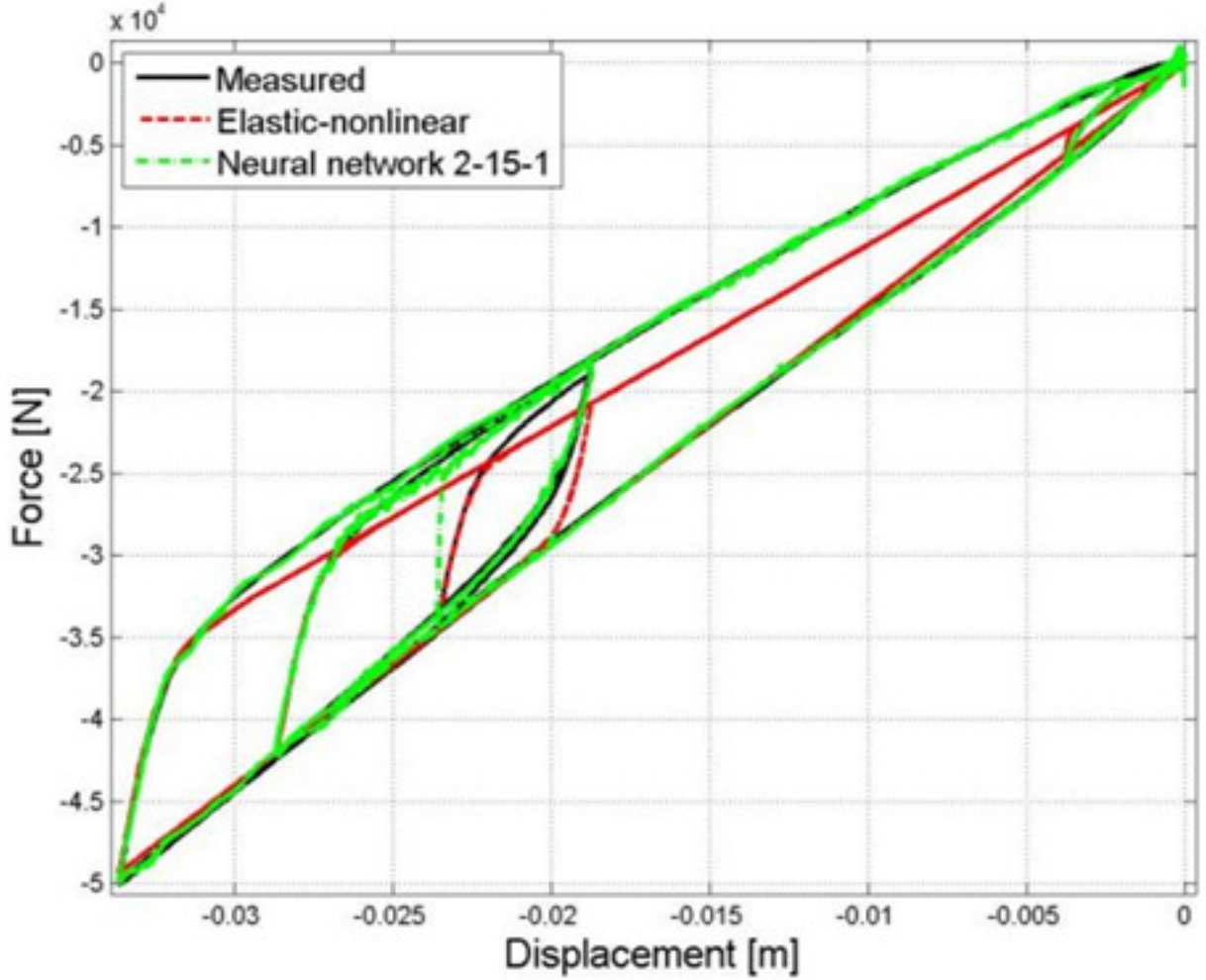
Validation metric based on relative error

$$RE = \left| \frac{p - m}{m} \right|$$

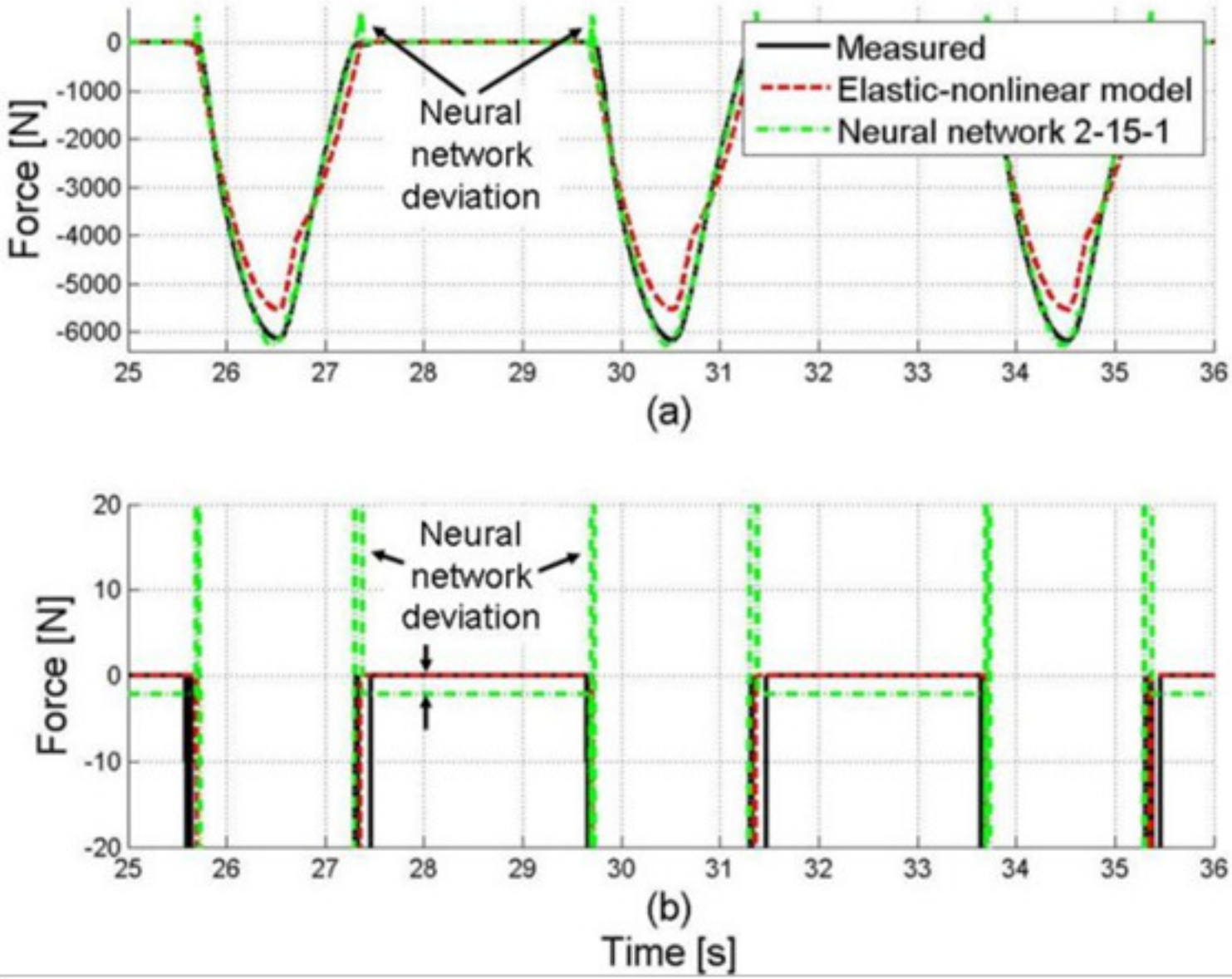


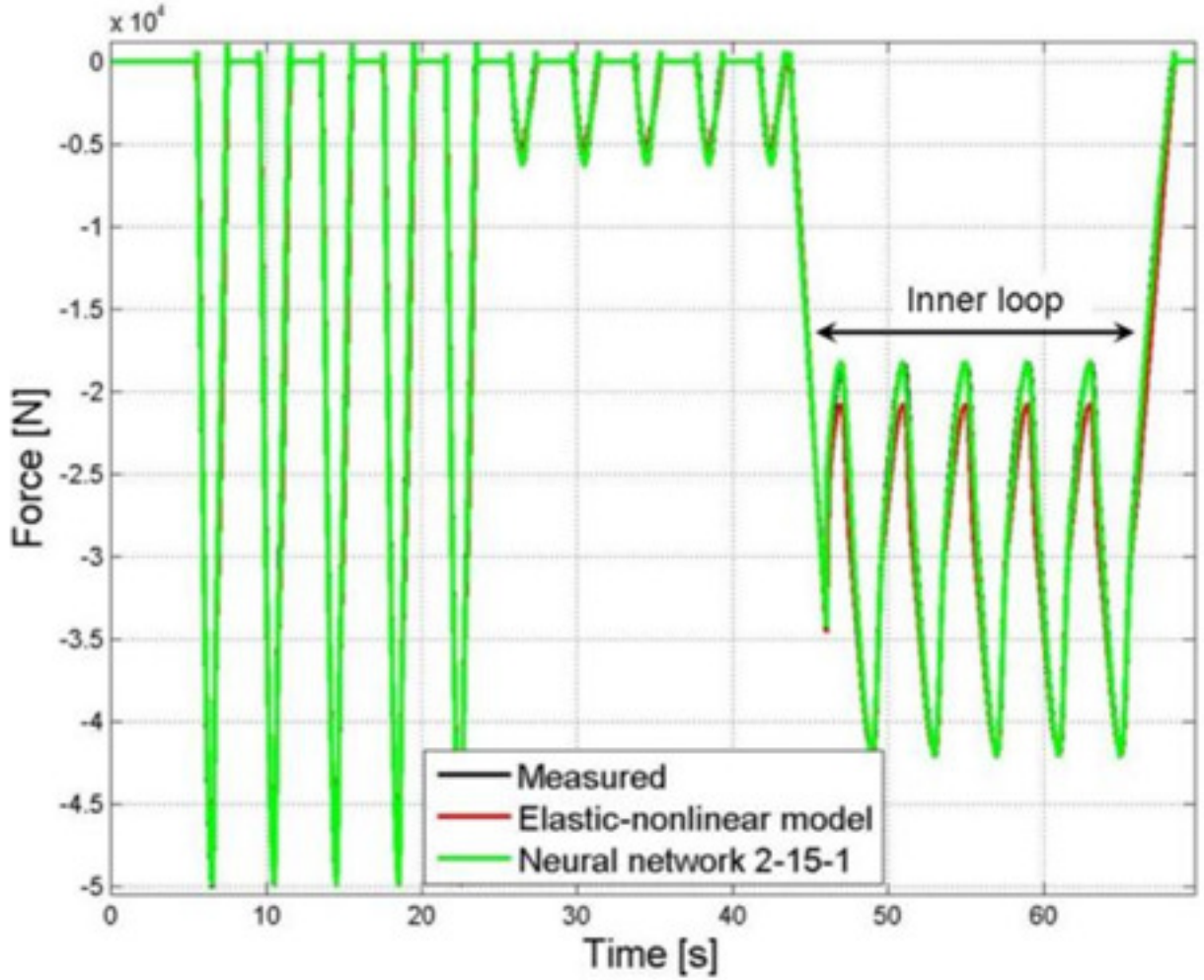
Validation metric based on relative error

- Periodic signals around zero
- Representation of agreement/disagreement



	Elastic-nonlinear model				Neural network model			
	S&G	**Russell**	***m%RE*^{m}**	***m%RE*^{s}**	**S&G**	**Russell**	***m%RE*^{m}**	***m%RE*^{s}**
Magnitude	2.6	2.17			-0.025	-0.021		
Phase	1.5	1.5			0.5	0.5		
Comprehensive	3.0	2.34	17.01 P(89.37)	10 P(76.01)	0.5	0.44	49.27 P(51.52)	10 P(49.67)


Measured
Elastic-nonlinear model
Neural network 2-15-1
Neural network deviation
Force [N]
0
-1000
-2000
-3000
-4000
-5000
-6000
25
26
27
28
29
30
31
32
33
34
35
36
(a)
Neural network deviation
Force [N]
20
10
0
-10
-20
(b)
Time [s]

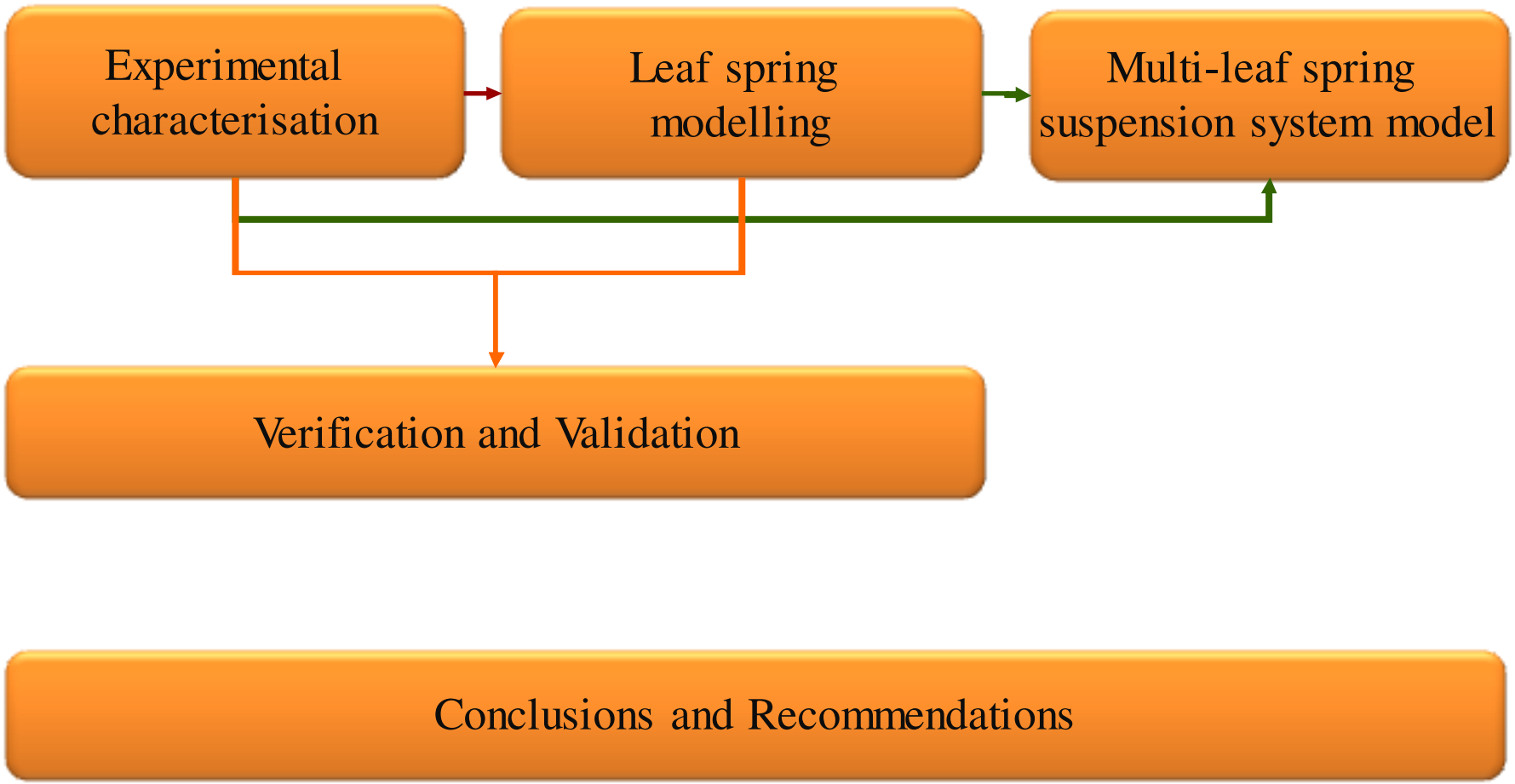


	Elastic-nonlinear model				Neural network model			
	S&G	Russell	$m\%RE^m$	$m\%RE^s$	S&G	Russell	$m\%RE^m$	$m\%RE^s$
Magnitude	3.42	2.82			-0.035	-0.03		
Phase	1.32	1.32			0.59	0.59		
Comprehensive	3.66	2.76	5.62 P(55.69)	10 P(72.85)	0.59	0.53	1.2 P(67.16)	10 P(99.3)

elastic-nonlinear model = 0.2429s

neural network model = 0.0792s

Conclusions



Recommendations

Experimental characterisation

- 6clc applied force's orientation as well as its point of application.
- force-displacement characteristics continuous loaded length change of the leaf spring

EPLS mode

- Ramberg-Osgood formulation
- Investigate alternative methods for handling the friction.
- Visualization of slip planes
- Theoretical stiffness of leaf springs

Recommendations

Neural network model

- inputs effect on training data required

Quantitative validation metric

- The *m%RE* validation metric should be extended to quantify model and experimental measurement uncertainties.

- quantify the tendency of the model to over-or under predict should be investigated and incorporated into the *m%RE*

Questions/Comments

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- To my **grandmother**, for teaching me commitment and consideration
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- To my girlfriend **Somarié**, for strengthening my believes and principles

I can do everything through Him who gives me strength

Philippians 4:13