

Structural Damage Diagnosis and prediction using Machine Learning and Deep Learning Models: Comprehensive Review of Advances

Amir Mosavi

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Structural Damage Diagnosis and prediction using Machine Learning and Deep Learning Models: Comprehensive Review of Advances

Amir Mosavi

School of Built the Environment, Oxford Brookes University, Oxford OX30BP, UK a.mosavi@brookes.ac.uk

The loss of integrity and adverse effect on mechanical properties can be concluded as attributing miro/macro-mechanics damage in structures especially in composite structures. Damage as a progressive degradation of material continuity in engineering predictions for any aspects of initiation and propagation, requires to be identified by a trustworthy mechanism to guarantee the safety of structures. Beside the materials design, the structural integrity and health are usually prone to be monitored clearly. One of the most powerful method for detection of damage is machine learning (ML). This paper presents the state of the art of ML methods and their applications in structural damage and prediction. Popular ML methods are identified and the performance and future trends are discussed.

Keywords: damage detection, machine learning, principal component analysis, composites, micromechanics of damage, continuum damage mechanics

Acronyms

ANN	Artificial neural network
ELM	Extreme learning machine
ML	Machine learning
SVM	Support vector machine
WNN	Wavelet neural networks
DL	Deep learning
ARIMA	Autoregressive integrated moving average
FFNN	Feed-forward neural networks
MLP	Multi layered perceptron

DT	Decision tree			
RSM	Response surface methodology			
BPNN	Back propagation neural network			
СМ	Centroid mean			
ANFIS	Adaptive neuro fuzzy inference system			
ANP	Analytic network process			
RF	Random forest			
NRTL	Non-random two-liquid			
RNN	Recurrent neural network			
PLS	Partial least squares			
DA	Discriminant analysis			
PCA	Principal component analysis			
LDA	Linear discriminant analysis			
SVR	Support vector regression			
LS	Least-squares			
SB	Sparse Bayesian			
MCDM	Multi criteria decision making			
GP	Genetic programming			
MLR	Multi linear regression			
SWARA	Step-wise Weight Assessment Ratio Analysis			
MOORA	Multi Objective Optimization by Ratio Analysis			
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1. Introduction

Structural damage diagnosis and prediction are of utmost importance in various scientific and engineering applications (Cha, Choi, Suh, Mahmoudkhani, & Büyüköztürk, 2018; Chen et al., 2019; Finotti, Cury, & Barbosa, 2019). Second paragraph on general damage detection methods and drawback to those methods (Hong et al., 2019; Huang & Wang, 2018; Jang, Lee, Park, & Baek, 2018; Kan et al., 2017; Krummenacher, Ong, Koller, Kobayashi, & Buhmann, 2018; Wang, Hu, & Zhai, 2018; Z. Zhang et al., 2019). Third paragraph on machine learning suitability and importance of machine learning and deep learning methods on this application (H. Li et al., 2019; Y. Z. Lin, Nie, & Ma, 2017; F. Ni, Zhang, & Chen, 2019; Patala, 2019; Pu, Apel, Liu, & Mitri, 2019; Quaranta et al., 2019). Fourth paragraph of this paper's contribution and the need for a comprehensive review. (Gordan, Razak, Ismail, & Ghaedi, 2017, 2018) reviews the general application of artificial intelligence methods including soft computing, data mining, optimization methods etc. However, there is a gap in research for a focused and comprehensive review on machine learning and deep learning models (S. Ren, Chen, Li, Chen, & Li, 2018; Salehi, Das, Biswas, & Burgueño, 2019).

There has been an enormous evolution in system modeling and intelligence after introducing the early models for deep learning. Deep learning methods very fast emerged and expanded applications in various scientific and engineering domains. Health informatics, energy, urban informatics, safety, security, hydrological systems modeling, economic, bioinformatics, and computational mechanics have been among the early application domains of deep learning. State of the art surveys on the data driven methods and machine learning algorithms, indicates that deep learning, along with the ensemble and hybrid machine learning methods are the future of data science. Further comparative studies report that deep learning models and hybrid machine learning models often outperform conventional machine learning models. Figure 1 represents the rapid rise in the applications of various deep learning methods during the past five years. Deep learning methods are fast evolving for higher performance. Literature includes adequate review papers on the progressing algorithms in particular application domains, e.g., renewable energy forecasting, cardiovascular image analysis, resolution imaging, radiology, 3D sensed data classification, 3D sensed data classification, multimedia analytics, sentiment classification, text detection, transportation systems, activity recognition in radar, hyperspectral, medical ultrasound analysis, image cytometry, and apache spark. However, a simplified list of deep learning methods has not been communicated so far. Thus, there is a gap in research in introducing the deep learning methods and summarize the methods and application in a brief, yet communicative paper. Consequently, this paper aims at providing a comprehensive list of the most popular deep learning methods and their notable applications. In every section, one deep learning method is introduced, and the notable applications related to that method are listed. The description of each deep learning method and the function of each building block is explained.

2. Survey methodology

The primary goal of this literature survey is to present the state of the art of ML models in the individual application areas of structural damage diagnosis. Accordingly, the research methodology has been developed to identify, classify and review the notable peer-reviewed articles in design and implementation of sustainable business models in top-level subject fields. The Web-of-Science and elsevier scopus are used for the implementation of the search queries of "defect or damage or crack" and "ml method_{1-n}" for title, abstract and keywords the relevant literatures are identified. the query of (title-abs-key (defect or damage or crack) and title-abs-key (ml method_{1-n})) in addition to the query of (title-abs-key (defect or damage or crack) and title-abs-key (dl method_{1-n})) would result in 21,933 documents. however, through auxiliary search keywords such as "mechanic* and structure*" in all fields of the paper we reduce the results to 4,669 documents making sure that the most relevant papers are identified, which forms our initial database. Reading in detail the articles' relevancy downed the numbers to 150 articles for the final consideration.

The research methodology follows a comprehensive and structured workflow based on a systematic database search and cross-reference snowballing. The flowchart of the research methodology is presented in figure 1. The method is considered as a modified version of review proposed by Easterby-Smith et al. (2015). In the first step the search queries explore the Thomson Reuters Web-of-Science and Elsevier Scopus databases. In the second step the abstract and keywords of the identified articles are browsed to identify the relevant literature and exclude the irrelevant ones. In step three the database of the relevant articles is created. In step four, the article is carefully read, and the category of the application is identified accordingly. In this step the expert-based knowledge and the initial preferences would influence the number and the type of the categories. In step five we decide on generating a new category and export the article in a new table of application domain or pass the article to step six where a category would host an article in its table. Once a category is created for a new article, in step seven, we pass that article to that category. In step eight we save the content of our database in various categories, update the content of the tables, and review the papers. This workflow will be repeated until sorting out all the papers.



Figure 1. Flowchart of the methodology of research

3. Machine learning methods

The survey methodology classifies the machine learning methods in seven groups, i.e. ANN-based, SVM-based, Tree-based models, Ensembles, Bayesians, Logistic regressions, and Neuro-Fuzzy. The last group is deep learning which has been considered separately. The notable papers have been reviewed in individual classes.

3.1 ANN

ANN can prepare general frameworks for analyzing damaged induced materials. Due to the fact that artificial neural networks have various applications such as accurate prediction of complex material behavior, it could be applied for damage detection and structural integrities in corresponding multiple-variable problems.

Reference	Year	Contribution	Application
		Accelerated discoveries	
Zhang Z., Hong		of mechanical properties	
Y., Hou B.,		of graphene using	
Zhang Z.,		machine learning and	
Negahban M.,		high-throughput	
Zhang J.	2019	computation	
		From in-situ monitoring	
		toward high-throughput	
Jafari-Marandi		process control: cost-	Additive manufacturing (AM);
R., Khanzadeh		driven decision-making	Artificial neural networks (ANN);
M., Tian W.,		framework for laser-	Porosity prediction; Self-organizing
Smith B., Bian		based additive	error-drive neural networks
L.	2019	manufacturing	(SOEDNN); Thermal history
Gomes G.F., de			
Almeida F.A.,		Optimized damage	Artificial neural networks; Composite
Junqueira D.M.,		identification in CFRP	plates; Damage identification; Inverse
da Cunha S.S.,		plates by reduced mode	problem; Sensor placement
Jr., Ancelotti		shapes and GA-ANN	optimization; Structural health
A.C., Jr.	2019	methods	monitoring
		An SHM approach using	Computational intelligence; Damage
		machine learning and	identification; Dynamic
Finotti R.P.,		statistical indicators	measurement; Structural dynamic;
Cury A.A.,		extracted from raw	Structural health monitoring;
Barbosa F.S.	2019	dynamic measurements	Vibration monitoring

Table 1. Notable ANN-based models for structural damage diagnosis and prediction

		Machine learning	
Pu Y., Apel		methods for rockburst	Artificial neural network; Burst
D.B., Liu V.,		prediction-state-of-the-art	liability: Deep learning: Rockburst
Mitri H.	2019	review	prediction; Support vector machine
		A simplified method to	
		predict fatigue damage of	Artificial neural network: Current:
		TTR subjected to short-	Fatigue damage: Riser: Top-
Wong E W C		term VIV using artificial	tensioned riser: Vortex-induced
Kim D K	2018	neural network	vibration
Nie W Zhao	2010	Performance based	
Z V Goh		support design for	
$\Delta T C$ Song		horseshee shaped rock	Artificial naural natwork:
A.I.C., Solig		asystem using 2D	Convergence confinement method:
Wi.K., Guo W., Zhu Y	2018	numerical analysis	Rock several Support design
	2018		Kock cavem, support design
		Least squares support	T
		vector mechanics to	Least squares support vector
		predict the stability	mechanics; Particle swarm
		number of rubble-mound	optimization; Rubble-mound
Gedik N.	2018	breakwaters	breakwater; Stability number
Rezaniaiee		Health monitoring of	Damage diagnosis; Finite element
Aqdam H.,		mooring lines in floating	method; Mooring lines; Radial basis
Ettefagh M.M.,		structures using artificial	neural networks; Structural health
Hassannejad R.	2018	neural networks	monitoring; Uncertainty
Cha YJ., Choi		Autonomous Structural	
W., Suh G.,		Visual Inspection Using	
Mahmoudkhani		Region-Based Deep	
S., Büyüköztürk		Learning for Detecting	
0.	2018	Multiple Damage Types	
		Application of deep	
		learning architectures for	
		accurate and rapid	
		detection of internal	Convolutional neural networks. Fruit
		mechanical damage of	quality detection: Hyperspectral
		blueberry using	transmittance image: Internal
Wang 7 Hu		hyperspectral	mechanical damage detection:
M Zhai G	2018	transmittance data	Machine learning
Krummenacher	2010		artificial neural networks: Machine
G Ong C S			learning: nattern analysis: railway
Koller S			accidents: railway safaty: statistical
Kohavashi S		Wheel Defect Detection	loorning: supervised loorning: support
Robayashi S., Puhmann I M	2018	wheel Defect Defection	vector mechines: wevelet transforms
Dullinalili J.WI.	2010	The notential englication	vector machines, wavelet transforms
AminShalmari		of montial application	
AIIIIIIISIIOKTAVI		or particle swarm	
A., Eskandar H.,		optimization algorithm	
Deraknsh A.M.,		for forecasting the air-	
Kad H.N.,	2010	overpressure induced by	
Ghanadi A.	2018	mine blasting	ANN; AOp; Blasting; PSO

			Data mining based	
			damage identification	Artificial neural network; Damage
	Gordan M.,		using imperialist	detection; Data mining; Hybrid
	Razak H.A.,		competitive algorithm	algorithm; Imperial competitive
	Ismail Z.,		and artificial neural	algorithm; Structural health
	Ghaedi K.	2018	network	monitoring
ſ			Exergetic performance	
			prediction of a roughened	Artificial neural network; Exergy
	Ghritlahre H.K.,		solar air heater using	analysis; Learning algorithm; Multi-
	Prasad R.K.	2018	artificial neural network	layer perceptron; Solar air heater
ľ	Rojas-Moraleda			
	R., Valous			
	N A Gowen		A frame-based ANN for	
	A Esquerre C		classification of	Artificial neural networks: Frame-
	Härtel S		hyperspectral images:	hased classification: Imaging
	Salinas I		assessment of mechanical	spectroscopy: Mechanical damage:
	O'Donnell C	2017	damaga in mushrooms	Soliont point detectors
ŀ	O Donnen C.	2017	Structural Demogra	Salient point detectors
			Detection with	
	Lin V 7 Nia		Automatic Easture	
	Lin IZ., Nie		Automatic Feature-	
	ZH., Ma H	2017	Extraction through Deep	
ŀ	W.	2017	Learning	
			Estimation of crack	
			propagation in polymer	Artificial neural network; Crack
	Çalık A.,		electrolyte membrane	propagation; Mechanical vibration;
	Yıldırım S.,		fuel cell under vibration	Polymer electrolyte membrane fuel
	Tosun E.	2017	conditions	cell
			Detecting damage in	Artificial Neural Network; Damage
	Tan Z.X.,		steel beams using modal	index; Damage location; Damage
	Thambiratnam		strain energy based	prediction; Damage scenarios;
	D.P., Chan		damage index and	Damage severity; Failure prevention;
	T.H.T., Abdul		Artificial Neural	Modal strain energy; Vibration based
	Razak H.	2017	Network	technique
ľ			Optimization of a	-
	Samareh H.,		nonlinear model for	
	Khoshrou S.H.,		predicting the ground	Artificial neural network; Blasting;
	Shahriar K.,		vibration using the	Genetic algorithm; Geo-mechanics
	Ebadzadeh		combinational particle	properties of rock mass: Ground
	M.M., Eslami		swarm optimization-	vibration: Particle swarm
	M.	2017	genetic algorithm	optimization
ŀ	Gordan M.		Recent developments in	Artificial neural network: Data
	Razak H A		damage identification of	mining technique. Genetic algorithm.
	Ismail 7		structures using data	Principal component analysis.
	Ghaedi K	2017	mining	Structural damage detection
ŀ	Ghucui IX.	2017	Identification of location	
	Choi C K Kim		and size of a defect in a	Active external moment: Artificial
		2016	and size of a defect in a	Active external moment, Attitudal
L	J.S., 100 H.H.	2010	structural system	neural network (AINN); Fault

		employing active external excitation and hybrid feature vector	diagnosis; Hidden Markov model (HMM); Structural system
		components in HMM	
Bissacot		· ·	
A.C.G., Salgado		Comparison of neural	
S.A.B.,		networks and logistic	
Balestrassi P.P.,		regression in assessing	
Paiva A.P.,		the occurrence of failures	Artificial neural networks; Fall of
Zambroni Souza		in steel structures of	metal structures; Logistic regression;
A.C., Wazen R.	2016	transmission lines	ROC curves; Transmission lines
, , , , , , , , , , , , , , , , , , ,		Comparative Analysis of	
		Soft Computing Models	
		in Prediction of Bending	
Guruprasad R.,		Rigidity of Cotton	ANFIS; ANN; Bending rigidity;
Behera B.K.	2015	Woven Fabrics	BPNN; GANN
		Structural modification	
Alves V., Cury		assessment using	
A., Roitman N.,		supervised learning	Damage assessment; Learning
Magluta C.,		methods applied to	algorithms; Pattern recognition;
Cremona C.	2015	vibration data	SHM; Symbolic data
		Numerical modeling of	
		time to corrosion induced	
Güneyisi E.M.,		cover cracking in	Experimental database; Modeling;
Mermerdaş K.,		reinforced concrete using	Reinforced concrete; Steel
Güneyisi E.,		soft-computing based	reinforcement corrosion; Time to
Gesoğlu M.	2015	methods	cover cracking
		Particle Swarm	
		Optimization based	
		support vector machine	
		for damage level	
Harish N.,		prediction of non-	
Mandal S., Rao		reshaped berm	Berm breakwater; Damage level;
S., Patil S.G.	2015	breakwater	Non-reshaped; PSO-SVM; SVM
		Structural damage	
		assessment using linear	Linear approximation; Maximum-
Meruane V.,		approximation with	entropy principle; Structural damage
Ortiz-Bernardin		maximum entropy and	assessment; Supervised learning
A.	2015	transmissibility data	algorithms

ANN based models include a great deal of models for damage modeling. (Alves, Cury, Roitman, Magluta, & Cremona, 2015; AminShokravi, Eskandar, Derakhsh, Rad, & Ghanadi, 2018; Bissacot et al., 2016; Çalık, Yıldırım, & Tosun, 2017; Cha et al., 2018; Choi, Kim, & Yoo, 2016; Finotti et al., 2019; Gedik, 2018; Ghritlahre & Prasad, 2018;

Gomes, de Almeida, Junqueira, da Cunha, & Ancelotti, 2019; Gordan et al., 2017, 2018; Güneyisi, Mermerdaş, Güneyisi, & Gesoğlu, 2015; Guruprasad & Behera, 2015; Harish, Mandal, Rao, & Patil, 2015; Jafari-Marandi, Khanzadeh, Tian, Smith, & Bian, 2019; Krummenacher et al., 2018; Y. Z. Lin et al., 2017; Meruane & Ortiz-Bernardin, 2015; Nie et al., 2018; Pu et al., 2019; Rezaniaiee Aqdam, Ettefagh, & Hassannejad, 2018; Rojas-Moraleda et al., 2017; Samareh, Khoshrou, Shahriar, Ebadzadeh, & Eslami, 2017; Tan, Thambiratnam, Chan, & Abdul Razak, 2017; Wang et al., 2018; Wong & Kim, 2018; Z. Zhang et al., 2019)

Authors	Year	Title	Author Keywords
			Acoustic emission; Failure mode
			identification; Glass fiber reinforced
			polymer (GFRP) laminate coupon; k -
		Studying Failure Modes of GFRP	means clustering; Multilayer perceptron;
Nair A., Cai C.S.,		Laminate Coupons Using AE Pattern-	Pattern recognition; Support vector
Kong X.	2019	Recognition Method	machine
Zhang Z., Hong		Accelerated discoveries of mechanical	
Y., Hou B., Zhang		properties of graphene using machine	
Z., Negahban M.,		learning and high-throughput	
Zhang J.	2019	computation	
			Acoustic emission; CFRP retrofitted RC
			beams; Failure mode identification; K-
		Acoustic emission pattern recognition	means clustering; Multilayer perceptron;
Nair A., Cai C.S.,		in CFRP retrofitted RC beams for	Pattern recognition; Support vector
Kong X.	2019	failure mode identification	machine
		Detection of Internal Defects in	Background thermal compensation by
Forero-Ramírez J		Carbon Fiber Reinforced Plastic Slabs	filtering (BTCF); Carbon fiber reinforced
C., Restrepo-Girón		Using Background Thermal	plastic (CFRP); Feature selection;
AD., Nope-		Compensation by Filtering and Support	Infrared thermography (IT); Support
Rodríguez SE.	2019	Vector Machines	vector machines (SVM)
		An SHM approach using machine	Computational intelligence; Damage
		learning and statistical indicators	identification; Dynamic measurement;
Finotti R.P., Cury		extracted from raw dynamic	Structural dynamic; Structural health
A.A., Barbosa F.S.	2019	measurements	monitoring; Vibration monitoring
		Machine learning methods for	Artificial neural network; Burst liability;
Pu Y., Apel D.B.,		rockburst prediction-state-of-the-art	Deep learning; Rockburst prediction;
Liu V., Mitri H.	2019	review	Support vector machine
		Least squares support vector	Least squares support vector mechanics;
		mechanics to predict the stability	Particle swarm optimization; Rubble-
Gedik N.	2018	number of rubble-mound breakwaters	mound breakwater; Stability number

Table. 2 Notable Support vectors (SVM) models

		An edge-feature-description-based	
		scheme combined with support vector	Edge feature description; Hybrid vision-
		machines for the detection of vortex-	based method; Support vector machines;
Lin TK.	2018	induced vibration	Vortex-induced vibration
			artificial neural networks; Machine
Krummenacher G.,			learning; pattern analysis; railway
Ong C.S., Koller			accidents; railway safety; statistical
S., Kobayashi S.,		Wheel Defect Detection with Machine	learning; supervised learning; support
Buhmann J.M.	2018	Learning	vector machines; wavelet transforms
Rojas-Moraleda			
R., Valous N.A.,			
Gowen A.,			Artificial neural networks; Frame-based
Esquerre C.,		A frame-based ANN for classification	classification; Imaging spectroscopy;
Härtel S., Salinas		of hyperspectral images: assessment of	Mechanical damage; Salient point
L., O'Donnell C.	2017	mechanical damage in mushrooms	detectors
Yi Q., Wang H.,		Laser ultrasonic quantitative	Dimension reduction; Laser ultrasonic;
Guo R., Li S.,		recognition based on wavelet packet	Quantitative recognition; SVM
Jiang Y.	2017	fusion algorithm and SVM	classification; Wavelet packet fusion
Alves V., Cury A.,			
Roitman N.,		Structural modification assessment	
Magluta C.,		using supervised learning methods	Damage assessment; Learning algorithms;
Cremona C.	2015	applied to vibration data	Pattern recognition; SHM; Symbolic data
			CFRP structural damage identification;
			Fiber bragg grating; Multi-class C-support
Lu S., Jiang M.,			vector classification; One-class support
Sui Q., Sai Y., Jia		Damage identification system of CFRP	vector machines; Principal component
L.	2015	using fiber bragg grating sensors	analysis
		Particle Swarm Optimization based	
Harish N., Mandal		support vector machine for damage	
S., Rao S., Patil		level prediction of non-reshaped berm	Berm breakwater; Damage level; Non-
S.G.	2015	breakwater	reshaped; PSO-SVM; SVM

SVM have gained popularity in modeling the damage. (Alves et al., 2015; Finotti et al., 2019; Forero-Ramírez, Restrepo-Girón, & Nope-Rodríguez, 2019; Gedik, 2018; Harish et al., 2015; Krummenacher et al., 2018; T. K. Lin, 2018; Lu, Jiang, Sui, Sai, & Jia, 2015; Nair, Cai, & Kong, 2019a, 2019b; Pu et al., 2019; Rojas-Moraleda et al., 2017; Yi, Wang, Guo, Li, & Jiang, 2017; Z. Zhang et al., 2019)

Tree-based models;

Decision trees (DTs), Classification and Regression Trees (CART)

AuthorsYearSource titleAuthor KeywordsAndrejiova M., Grincova A.,Engineering FailureClassification model; Damage; Decision tree; Regression analysis; Rubber-textileMarasova D.2019AnalysisDia A., Dieng L., Gaillet L., Gning P.B.2019HeliyonMechanical engineeringdamage-sensitive features; real- time damage detection; Recursive singular spectral analysis; Rubber and the damage detection; Recursive singular spectral analysis; sturbural health monitoring; time-varying B., Pakrashi V.Structural Health Health HealthNoori Hoshyar A., Samali B., Liyanapathirana R., D.B., Pevarat D.O.2019Monitoring MonitoringBeyew A.C., Roueche D.B., Pevarat D.O.2019Monitoring Monitoringmonitoring; time-varying analysis; structural health sensors; Structural health sensorsPérez-Ruiz M.R., Garrido-Lard M., Suffrez-Guanter2018Convolutional neural networks; Fruir quality detection; Hyperspectral transmittance inage; Internal mechanical damage detection; Hyperspectral transmittance inage; Internal mechanical <br< th=""><th></th><th></th><th></th><th></th></br<>				
Andrejova M., Grincova A., Marasova D.Engineering Failure AnalysisClassification model; Damage; Decision tree; Regression analysis; Rubber-textile conveyor beltDia A., Dieng L., Gaillet L., Gning P.B.2019HeliyonAccoustics; Materials science; mechanical engineeringMarasova D.2019HeliyonMechanical engineering damage-sensitive features; real- time damage detection; Recursive singular spectral analysis; structural bealth monitoring; time-varying autoregressive modelingBhowmik B., Krishnan M., Hazra B., Pakrashi V.2019Monitoring Monitoringautoregressive modeling mother wavelets; severity analysis; structural bealth monitoring; time-varying autoregressive modeling mother wavelets; severity analysis; smart aggregate Health sensors; Structural health sensors; Canopy volume; Fruit damage; Casanova L., Valero C., Marthez-Guanter J., Morales-Sillero A.2018Canopy volume; Fruit damage; canopy volume; Fruit damage; Laser scanning; Monitoring; Hyperspectral transmittance image; Internal mechanical damage detection; Hyperspectral transmittance image; Internal mechanica	Authors	Year	Source title	Author Keywords
Andrejiova M., Grincova A., Marasova D.Engineering FailureDecision tree; Regression analysis; Rubber4extile conveyor beltDia A., Dieng L., Gaillet L., Gning P.B.2019HeliyonMechanical engineeringBiowmik B., Krishnan M., Hazra B., Pakrashi V.2019HeliyonMechanical engineeringBhowmik B., Krishnan M., Hazra B., Pakrashi V.2019Monitoring Monitoringdamage-sensitive features; real- time damage detection; Recursive singular spectral analysis; structural health monitoring; time-varying autoregressive modelingNoori Hoshyar A., Samali B., L. Structural Taghariyour S.2019Monitoring Monitoringdamage index; de-noising; moniter wavelets; severity analysis; smart agregate sensors; Structural health monitoring; wavelet de-noisingPercer.Ruiz M. Rallo P., Jiménez M.R., Garrido-Izard M., Suárez M.P., C., Martínez-GuanterNatural Hazards ReviewCanopy volume; Fruit damage; Laser scanning; Monitoring; Olea europaca; Olive harvester fruit quality detection; Hyperspectral transmittance image; Internal mechanical damage detection; Hyperspectral transmittance image; Internal mechanical damage detection; Hyperspectral transmittance image; (TPA); Fuzzy set theory; Linguistic variables; Oil and gas pielines; Safety a spectral transmittance image; Internal mechanical damage detection; Machine learningMarage M.G., Sadiq R., Tesfamariam S.2016Structure and Infrastructure gas specine; Buckling; CFPA; Damage; Ausite variables; Oil and gas pielines; Safety as specine; Buckling; CFPA; Damage; Huyerspectron; Hyperspectron; Hyperspectron; Hype				Classification model; Damage;
Grincova A., Marasova D.Failure 2019analysis; Rubber-textile conveyor heltDia A., Dieng L., Gaillet L., Gning P.B.2019HeliyonAcoustics; Materials science; Mechanical engineering damage-sensitive features; real- time damage detection; Recursive singular spectral analysis; structural health monitoringBhowmik B., Krishnan M., Hazra B., Pakrashi V.Structural Healthmonitoring; ime-varying autorgressive modeling damage index; de-noising; mother wavelets; severity analysis; structural health monitoring; ime-varying autorgressive modelingNoori Hoshyar A., Samali B., Liyanapathirana R., Taghavipour S.Structural Health Healthanalysis; structural health monitoring; ime-varying autorgressive modeling damage index; de-noising mother wavelets; severity analysis; structural health monitoring; wavelet de-noising mother wavelets; severity analysis; Rubber-textile canapysis; structural health monitoring; wavelet de-noisingNoori Hoshyar A., Samali B., Liyanapathirana R., Taghavipour S.2019Monitoring Monitoring monitoring; wavelet de-noisingB., Prevatt D.O. Suárez M.R., Garrido-Izard M., Suárez M.P., Casanova L., Valero C., Martínez-Guanter J., Morales-Sillero A.2018Canopy volume; Fruit damage; Laser scanning; Monitoring; J., Morales-Sillero A.Wang Z., Hu M., Zhai G. C., Hwang J.H., Jung J.T.2017Garan) (Garan)Canopy volume; Fruit damage; Laser scanning; Monitoring; Garange, CRP; Damage; Hyperspectral transmittance image; Iterand mechanical damage detection; Hyperspectral transmittance image; Iteratical manage detection; Hyperspectra	Andreijova M.,		Engineering	Decision tree: Regression
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J., Morales-Sillero A.2018(Switzerland)Olea europaea; Olive harvesterImage: J., Morales-Sillero A.2018Convolutional neural networks; Fruit quality detection; Hyperspectral transmittance image; Internal mechanical damage detection; Machine learningWang Z., Hu M., Zhai G.Sensors 2018damage detection; Machine learningG.2018(Switzerland)learningKim C.S., Hwang J.H., Jung J.T.Information 20173-point bending specimen; Buckling; CFRP; Damage; RestorationKim G., Sadiq R., Tesfamariam S.2016Structure and Infrastructure EngineeringBayesian belief network (BBN); Fault tree analysis (FTA); Fuzzy set theory; Linguistic variables; Oil and gas pipelines; Safety assessment; UncertaintyDorval A.D., Meredieu C., Danjon F.2016Annals of BotanyAcclimation; Biomechanics; Flexural stiffness; Forest tree;	C., Martinez-Guanter	2010	Sensors	Laser scanning; Monitoring;
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Wang Z., Hu M., ZhaiSensorsFruit quality detection; Hyperspectral transmittance image; Internal mechanical damage detection; Machine learningG.2018(Switzerland)learningG.2018(Switzerland)learningKim C.S., Hwang J.H., Jung J.T.Information 2017Buckling; CFRP; Damage; Bayesian belief network (BBN); Fault tree analysis (FTA); Fuzzy set theory; Linguistic variables; Oil and gas pipelines; Safety Tesfamariam S.Structure and Infrastructure EngineeringLinguistic variables; Oil and gas pipelines; Safety assessment; UncertaintyDorval A.D., Meredieu C., Danjon F.2016Annals of BotanyAcclimation; Biomechanics; Flexural stiffness; Forest tree;				Convolutional neural networks;
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Wang Z., Hu M., ZhaiSensorsimage; Internal mechanical damage detection; MachineG.2018(Switzerland)learningKim C.S., HwangInformation3-point bending specimen; Buckling; CFRP; Damage; RestorationJ.H., Jung J.T.2017(Japan)RestorationKim G., Sadiq R.,Structure and InfrastructureLinguistic variables; Oil and gas pipelines; Safety assessment; UncertaintyDorval A.D., Meredieu C., Danjon2016Annals of BotanyF.2016BotanyFlexural stiffness; Forest tree;				Hyperspectral transmittance
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Kabir G., Sadiq R.,Structure andLinguistic variables; Oil andTesfamariam S.2016Engineeringassessment; UncertaintyDorval A.D.,Annals ofAcclimation; Biomechanics;F.2016BotanyFlexural stiffness; Forest tree;				(BBN): Fault tree analysis
Kabir G., Sadiq R.,Structure andLinguistic variables; Oil andTesfamariam S.2016Engineeringassessment; UncertaintyDorval A.D.,Annals ofAcclimation; Biomechanics;F.2016BotanyFlexural stiffness; Forest tree;				(\mathbf{ETA}) , Fuzzy set theory
Kabir G., Sadiq R., Tesfamariam S.Infrastructure 2016gas pipelines; Safety assessment; UncertaintyDorval A.D., Meredieu C., DanjonAnnals of 2016Acclimation; Biomechanics; F.F.2016BotanyFlexural stiffness; Forest tree;			Structure and	(11A), FUZZY SET UPOLY,
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Testamariam S.2016Engineeringassessment; UncertaintyDorval A.D., Meredieu C., DanjonAnnals of F.3D root architecture; Acclimation; Biomechanics; Flexural stiffness; Forest tree;	Kabir G., Sadiq K.,	2015	Infrastructure	gas pipelines; Safety
Dorval A.D., Meredieu C., DanjonAnnals of 20163D root architecture; Acclimation; Biomechanics; Flexural stiffness; Forest tree;	Testamariam S.	2016	Engineering	assessment; Uncertainty
Meredieu C., DanjonAnnals ofAcclimation; Biomechanics;F.2016BotanyFlexural stiffness; Forest tree;	Dorval A.D.,			3D root architecture;
F. 2016 Botany Flexural stiffness; Forest tree;	Meredieu C., Danjon		Annals of	Acclimation; Biomechanics;
	F.	2016	Botany	Flexural stiffness; Forest tree;

			Maximum tensile load; Pinus
			pinaster; Soil depth; Toppling;
			Tree anchorage; Windthrow
			Coppice stands;
Favillier A., Lopez-			Dendrogeomorphology; Forest-
Saez J., Corona C.,			rockfall interactions; French
Trappmann D., Toe			Alps; Recurrence intervals;
D., Stoffel M., Rovéra			Submontane broadleaved
G., Berger F.	2015	Geomorphology	species
Alves V., Cury A.,			Damage assessment; Learning
Roitman N., Magluta		Engineering	algorithms; Pattern recognition;
C., Cremona C.	2015	Structures	SHM; Symbolic data

(Alves et al., 2015; Andrejiova, Grincova, & Marasova, 2019; Bhowmik, Krishnan, Hazra, & Pakrashi, 2019; Dia, Dieng, Gaillet, & Gning, 2019; Dorval, Meredieu, & Danjon, 2016; Egnew, Roueche, & Prevatt, 2018; Favillier et al., 2015; Kabir, Sadiq, & Tesfamariam, 2016; Kim, Hwang, & Jung, 2017; Noori Hoshyar, Samali, Liyanapathirana, & Taghavipour, 2019; Pérez-Ruiz et al., 2018; Wang et al., 2018; Z. Zhang et al., 2019)

Table. 4 Notable ensembl	es models	including	it includes	boosting	and	bagging	for
making ensembles							

Authors	Title	Year	Author Keywords
	Evolution of pore ensemble in solid and		Aluminum melt; Dynamic tensile
	molten aluminum under dynamic tensile		fracture; High-rate stretching;
Mayer A.E., Mayer	fracture: Molecular dynamics simulations		Mechanical model; Molecular
P.N.	and mechanical models	2019	dynamics; Solid aluminum
Uzay C., Geren N.,	Bending behavior of sandwich structures		ANOVA; Failure modes; Flexural
Boztepe M.H.,	with different fiber facing types and		properties; Sandwich structures; Ttree-
Bayramoglu M.	extremely low-density foam cores	2019	point bending
	Mixed-mode crack propagation tests of		
Panettieri E.,	composite bonded joints using a dual-		Composite bonded joints; Debonding;
Leclerc G., Jumel J.,	actuator load frame – Constant and		Dual-actuator system; Fracture
Guitard J.	variable G II /G I conditions	2018	toughness; Mixed-mode
	Application of deep learning		Convolutional neural networks; Fruit
	architectures for accurate and rapid		quality detection; Hyperspectral
	detection of internal mechanical damage		transmittance image; Internal
Wang Z., Hu M.,	of blueberry using hyperspectral		mechanical damage detection;
Zhai G.	transmittance data	2018	Machine learning
Fakih M.A.,	Detection and assessment of flaws in		CT scanning; Finite element analysis;
Mustapha S., Tarraf	friction stir welded joints using ultrasonic	2018	Friction stir welding; Lamb waves;

J., Ayoub G.,	guided waves: experimental and finite		Structural health monitoring; Weld
Hamade R.	element analysis		inspection
Froustey C.,			
Naimark O.B.,			
Panteleev I.A.,			
Bilalov D.A.,			
Petrova A.N.,	Multiscale structural relaxation and		adiabatic shear; dynamic loading;
Lyapunova E.A.	adiabatic shear failure mechanisms	2017	microdefects
	Reliability of MEMS accelerometers for		
Tanırcan G., Alçık	instrumental intensity mapping of		
H., Beyen K.	earthquakes	2017	
	Adaptive Multiscale Noise Control		
	Enhanced Stochastic Resonance Method		
	Based on Modified EEMD with Its		
Li J., Zhang J.	Application in Bearing Fault Diagnosis	2016	
	Wafer defect detection and recognition		Gaussian mixture model (GMM);
	based on local and nonlocal linear		Manifold learning; Pattern
Yu JB., Lu XL.,	discriminant analysis and dynamic		recognition; Semiconductor
Zong WZ.	ensemble of gaussian mixture models	2016	manufacturing; Wafer defect
Sokovikov M.,			
Bilalov D., Oborin			
V., Chudinov V.,			
Uvarov S.,			Dynamic loading; Microdefects;
Bayandin Y.,	Structural mechanisms of formation of		Numerical modeling; Plastic strain
Naimark O.	adiabatic shear bands	2016	localization
			Damage detection; Ensemble
			empirical mode decomposition;
	Structural damage detection based on		Hilbert-huang transform;
Ren YC., Weng P.	improved Hilbert-Huang transform	2015	Instantaneous frequency
Ovid'Ko I.,			
Sheinerman A.,			
Skiba N.,	Twin boundary migration and nanocrack		Cracks; Defects; Fracture; Modeling;
Krasnitiskiy S.,	generation in ultrafine- grained materials		Nanotwinned materials; Plastic
Smirnov A.	with nanotwinned structure	2015	deformation; Yield strength

(Fakih, Mustapha, Tarraf, Ayoub, & Hamade, 2018; Froustey et al., 2017; J. Li & Zhang, 2016; Mayer & Mayer, 2019; Ovid'Ko, Sheinerman, Skiba, Krasnitiskiy, & Smirnov, 2015; Panettieri, Leclerc, Jumel, & Guitard, 2018; Y. C. Ren & Weng, 2015; Sokovikov et al., 2016; Tanırcan, Alçık, & Beyen, 2017; Uzay, Geren, Boztepe, & Bayramoglu, 2019; Wang et al., 2018; Yu, Lu, & Zong, 2016)

Authors	Year	Author Keywords	Title
Sha G., Radzieński M., Cao M., Ostachowicz W.	2019	Bayesian data fusion; Damage growth monitoring; Damage localization; Relative natural frequency change; Severity estimation	A novel method for single and multiple damage detection in beams using relative natural frequency changes
Chattopadhyay P., Mondal S., Ray A., Mukhopadhyay A.	2019		Dynamic Data- Driven Combustor Design for Mitigation of Thermoacoustic Instabilities
Yang D.Y., Frangopol D.M.	2018	Bayesian network; crack growth; decision- making; Fatigue; influence diagram; life-cycle	Evidence-based framework for real- time life-cycle management of fatigue-critical details of structures
Ye D., Hong G.S., Zhang Y., Zhu K., Fuh J.Y.H.	2018	Additive manufacturing; Deep belief networks; Defect detection; Fast Fourier transform	Defect detection in selective laser melting technology by acoustic signals with deep belief networks
Ebrahimian H., Astroza R., Conte J.P., Papadimitriou C.	2018	Bayesian method; direct differentiation method; joint parameter and input estimation; nonlinear finite element model; output-only system identification; structural health monitoring	Bayesian optimal estimation for output-only nonlinear system and damage identification of civil structures
Wu X., Zeng X., Huang J., Song HQ.	2017	Bayesian network; Finite element analysis; Reliability growth; Solid rocket motor; Structure optimization	Research on Tail Structure Optimization for Solid Rocket Motor
Liu Y., Shuai Q., Zhou S., Tang J.	2017	Damage prognosis; finite element methods (FEMs); hierarchical Bayesian model; Markov	Prognosis of Structural Damage Growth Via

Table 5. Notable Bayesians Models

		chain Monte Carlo (MCMC) method; structural health monitoring	Integration of Physical Model Prediction and Bayesian Estimation
Ni Y., Lu X., Lu W.	2017	Bayesian; High-rise building; Modal identification; Shaking table test; Vibration test	Operational modal analysis of a high- rise multi-function building with dampers by a Bayesian approach
Ebrahimian H., Astroza R., Conte J.P., de Callafon R.A.	2017	Bayesian inference; Gradient-based optimization; Model updating; Nonlinear finite element model; Nonlinear system identification; Uncertainty quantification	Nonlinear finite element model updating for damage identification of civil structures using batch Bayesian estimation
Kabir G., Sadiq R., Tesfamariam S.	2016	Bayesian belief network (BBN); Fault tree analysis (FTA); Fuzzy set theory; Linguistic variables; Oil and gas pipelines; Safety assessment; Uncertainty	A fuzzy Bayesian belief network for safety assessment of oil and gas pipelines
Yazdanipour M., Pourgol- Mohammad M.	2016	Bayesian approach; Crack length distribution; Fatigue crack growth; Probabilistic modeling; Propagation of uncertainty	Stochastic fatigue crack growth analysis of metallic structures under multiple thermal- mechanical stress levels
Seuba J., Deville S., Guizard C., Stevenson A.J.	2016	Ceramics; Mechanical properties; Mechanical reliability; Porous materials; Weibull	The effect of wall thickness distribution on mechanical reliability and strength in unidirectional porous ceramics
Alves V., Cury A., Roitman N., Magluta C., Cremona C.	2015	Damage assessment; Learning algorithms; Pattern recognition; SHM; Symbolic data	Structural modification assessment using supervised learning methods applied to vibration data

Baneen U.,		Bayesian; Curvature mode shapes; Damage
Guivant J.E.	2015	detection; Kernels; Plate-type structure.

A 2D Bayesian approach for damage detection in platetype structures

(Chattopadhyay, Mondal, Ray, & Mukhopadhyay, 2019; Ebrahimian, Astroza, Conte, & de Callafon, 2017; Ebrahimian, Astroza, Conte, & Papadimitriou, 2018; Kabir et al., 2016; Liu, Shuai, Zhou, & Tang, 2017; Y. Ni, Lu, & Lu, 2017; Seuba, Deville, Guizard, & Stevenson, 2016; Sha, Radzieński, Cao, & Ostachowicz, 2019; Wu, Zeng, Huang, & Song, 2017; Yang & Frangopol, 2018; Yazdanipour & Pourgol-Mohammad, 2016; Ye, Hong, Zhang, Zhu, & Fuh, 2018)

Logistic regressions

Authors	Title	Year	Author Keywords
Egnew A.C.,	Linking Building Attributes and		
Roueche D.B.,	Tornado Vulnerability Using a		
Prevatt D.O.	Logistic Regression Model	2018	
			Dual sensing; Failure
	Failure detection technique under		detection; Fatigue loading;
Jang DW., Lee	random fatigue loading by		Machine learning;
S., Park JW.,	machine learning and dual sensing		Prognostics and Health
Baek DC.	on symmetric structure	2018	Management (PHM)
Bissacot			
A.C.G., Salgado			
S.A.B.,	Comparison of neural networks		
Balestrassi P.P.,	and logistic regression in		Artificial neural networks;
Paiva A.P.,	assessing the occurrence of		Fall of metal structures;
Zambroni Souza	failures in steel structures of		Logistic regression; ROC
A.C., Wazen R.	transmission lines	2016	curves; Transmission lines
Regan T.,			Health Monitoring; Logistic
Canturk R.,			Regression; Machine
Slavkovsky E.,	Wind turbine blade damage		Learning; Support Vector
Niezrecki C.,	detection using various machine		Machine; Wind Turbine
Inalpolat M.	learning algorithms	2016	Blades
Gauthier F.,	Forecasting method of ice blocks		Degree-day; Ice avalanche;
Hétu B., Allard	fall using logistic model and		Ice blocks fall; Logistic
M.	melting degree-days calculation:	2015	regression; Predictive model

Table 6. Notable logistic regressions

	a case study in northern Gaspésie,		
	Québec, Canada		
Zhang W., Shen			
S., Basak P.,			
Wen H., Wu S.,	Development of predictive		
Faheem A.,	models for initiation and		
Mohammad	propagation of field transverse		
 L.N.	cracking	2015	
Wazen R.N.,			
Fernandes			Dropped structures; Logistic
Fernandes T.S.P., Aoki	Evaluation of the susceptibility of		Dropped structures; Logistic regression; Metallic
Fernandes T.S.P., Aoki A.R., De Souza	Evaluation of the susceptibility of failures in steel structures of		Dropped structures; Logistic regression; Metallic structures; Rough sets;
Fernandes T.S.P., Aoki A.R., De Souza W.E.	Evaluation of the susceptibility of failures in steel structures of transmission lines	2013	Dropped structures; Logistic regression; Metallic structures; Rough sets; Transmission lines

(Bissacot et al., 2016; Egnew et al., 2018; Gauthier, Hétu, & Allard, 2015; Jang et al., 2018; Regan, Canturk, Slavkovsky, Niezrecki, & Inalpolat, 2016; Wazen, Fernandes, Aoki, & De Souza, 2013; W. Zhang et al., 2015)

Neuro-Fuzzy

Authors	Title	Year	Author Keywords
	Algorithm for estimating		
	online bearing fault upon		adaptive neuro-fuzzy inference system
	the ability to extract		(ANFIS)-based damage identification; AI
Tran Q.T.,	meaningful information		for estimating damage; identifying bearing
Nguyen S.D.,	from big data of intelligent		damage; singular spectrum analysis (SSA)
Seo TI.	structures	2019	for identifying damage
	Shear failure capacity		Adaptive neuro-fuzzy inference system
	prediction of concrete		(ANFIS); Concrete beam-column joint;
Naderpour	beam-column joints in		Group method of data handling (GMDH);
H., Mirrashid	terms of ANFIS and		Shear capacity; Soft computing;
М.	GMDH	2019	Vulnerability
	Predicting the collapsibility		
Hashemineja	potential of unsaturated		Adaptive neural fuzzy inference system;
d M.M.,	soils using adaptive neural		Collapsibility potential; Gaussian
Sohankar N.,	fuzzy inference system and		membership function; Particle swarm
Hajiannia A.	particle swarm optimization	2018	optimization; Soft computing
			Beam; Damage detection; Grid
Aydin K.,	Damage detection in		partitioning; Neuro fuzzy system;
Kisi O.	structural beam elements	2015	Subtractive clustering

	using hybrid neuro fuzzy		
	systems		
	Comparative Analysis of		
	Soft Computing Models in		
Guruprasad	Prediction of Bending		
R., Behera	Rigidity of Cotton Woven		ANFIS: ANN: Bending rigidity: BPNN:
B.K.	Fabrics	2015	GANN
			adaptive neuro-fuzzy inference system;
Nanda J., Das	Influence of multi-		experimental analysis; mode shape;
L.D., Das S.,	transverse crack on		multiple cracks; natural frequency; shaft;
Das H.C.	cantilever shaft	2015	Vibration
	3rd International		
	Conference on Civil		
[No author	Engineering and		
name	Transportation, ICCET		
available]	2013	2014	
	2013 International		
[No author	Conference on Mechanical		
name	and Electronics		
available]	Engineering, ICMEE 2013	2013	
	2013 2nd International		
	Conference on Manufacture		
[No author	Engineering, Quality and		
name	Production System,		
available]	ICMEQP 2013	2013	
Adoko A.C.,			ANFIS; Mamdani fuzzy inference system;
Gokceoglu	Knowledge-based and data-		Prediction modeling in rock engineering;
C., Wu L.,	driven fuzzy modeling for		Rockburst; Takagi-Sugeno fuzzy inference
Zuo Q.J.	rockburst prediction	2013	system
	-		

(Adoko, Gokceoglu, Wu, & Zuo, 2013; Aydin & Kisi, 2015; Guruprasad & Behera, 2015; Hasheminejad, Sohankar, & Hajiannia, 2018; Naderpour & Mirrashid, 2019; Nanda, Das, Das, & Das, 2015; Tran, Nguyen, & Seo, 2019)

Conclusions

Deep learning methods are fast-evolving. Some of them have advanced to be specialized in a particular application domain. However, there is a gap in research in introducing the deep learning methods and summarize the methods and application in a single paper. Consequently, this paper aims at providing a comprehensive list of the most popular deep learning methods and provide notable applications. CNN, RNN, DAE, DBNs, LSTM methods have been identified as the most popular deep learning method. The description of each deep learning method and the function of each building block of them is explained.

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