Optimization Algorithm and the Inverse Problems Applied to the Structural Damage Identification in Steel Beams with the use of FEM and Experimental Data

Brunno E. Sobrinho[1], Gilberto Gomes[1], Ramon S. Y. R. C. Silva[1]

[1]*Dept. of Civil and Environmental Engineering, Graduate Program in Structural Engineering and Civil Construction, University of Brasilia*
Campus Darcy Ribeiro SG-12, 70910-900, Distrito Federal, Brazil
brunno.emidio@aluno.unb.br, ggomes@unb.br, ramon@unb.br

Abstract. Optimization problems in academia and industry are recurrent, in addition the structural elements conditions over their lifetime when in use acquired differents damages from their natural deterioration or even because of the exceptional causes that can cause these different magnitudes of damage. In this sense, to combine the damages identification through optimization processes in the continuous search for more adequate means and consequently the improvement of the available informations that characterizes the problems under essential study, and constitutes one of the current engineering requirements, considering the evolutionary state of the structural elements when in use. In this work, it is proposed the adjustment of experimentally steel beams structures tested, from a static analysis by the Finite Element Method (FEM) using ANSYS© to obtain displacements, with the use of inverse problems and an optimization method. From the adjusted models, damages in the structures are simulated (elements stiffness properties reduction) and then an optimization technique and damage identification are applied through the Differential Evolution Method. The modelled and experimentally steel beams structures tested showed mostly consistent results and the DE technique showed good potential for solving damage identification problems using Inverse Problems, achieving convergence in almost all cases.

Keywords: Optimization, Finite Element Method, Inverse Problems, Damage Identification, Differential Evolution.

1 Introduction

A multitude of engineering works that are in advanced ages or even that have been poorly designed and executed, beginning to manifest various deteriorations from differents situations, facts that demonstrate the importance of the damage forecasts areas.

This research seeks to continue the achieved advances in the areas of Damage Prognosis (DP) and Structural Health Monitoring (SHM) of the engineering, with optimal processes aiming at increasingly better solutions to the arise problems.

As stated in Yang et al. (2016) [1], optimization analyses are crucially important in the design process to find a good balance between economy and safety in all areas of engineering.

Another determinant point, depends of the cost / objective function specification, defined as the relationship between the experimental and numerical results, they should efficiently conduct the optimization process, having as main properties, for example, the curve of experimental data points and all experimental curves should have equal opportunities to be optimized and different units and/or the number of curves in each sub-objective should not affect the overall performance of the accessory.

The use of Differential Evolution Method to detect damage in steel beams on the basis of numerical and experimental results are proposes in this paper in the context of the Structural Health Monitoring Methods.

2 Theoretical References

2.1 Optimization Algorithms

The optimizer idea is make successive changes in the damage variables of the damaged model to find the tested elements damage. The process that involves this procedure is composed by the Inverse Problem that will plot the state maintains structure.
Its efficiency is achieved by choosing an appropriate objective function and design variables. An optimization problem general scheme, demonstrated in Gomes *et. al.* (2016) [2], can be observed in Fig. 1 below.

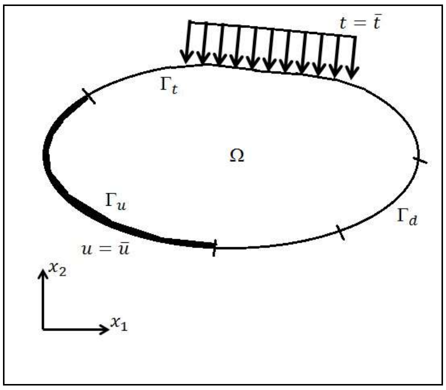


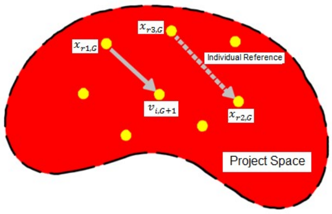
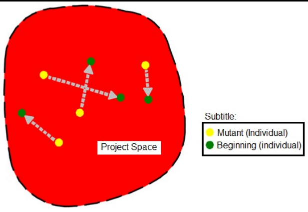
Figure 1. Two-dimensional elastic structure where: Ω - domain; Γ_u - boundary with fixed displacements $(\bar{\mathbf{u}} = \mathbf{0})$; Γ_t - boundary with applied tractions; Γ_d - de - sign boundary $(\bar{\mathbf{t}} = \mathbf{0})$; $\mathbf{u}$ - displacements; $\mathbf{t}$ - tractions; x_i - Cartesian coordinates

The used optimization techniques for the damage detection procedure essentially follow the measurement of displacement from the damaged structure, the displacement calculation from the undamaged model, the convergence check and whether this criterion is met, the shift to a new point, the displacement calculation at the new point and the iteration from the convergence analysis. The advantages are the low sensitivity to noise compared to other techniques. The static displacements and the stiffness of each element are used, since the damages in the structures are usually defined as a stiffness reduction of the element (Choi, 2002) [3]).
In this context, from the structures modeled by the Finite Element Method (FEM) based on static experimental data (displacements), through inverse problems and optimization methods the adjusted models will be simulated damages in the structures, testing their efficiency for such purpose and seeking the development of an ideal optimizer.

2.2 Differential Evolution Method

According to Storn and Price (1995) [4], proponents of the Differential Evolution (DE) method, the classic version of this algorithm is very simple and presents some advantages, such as: it has only three control parameters; it works with real domains, that is, it does not require the design variables to be coded in binary numbers; it presents good convergence properties and can be easily adapted for use in parallel computing.
In Sobrinho *et. al* (2020) [5], the DE method uses algorithms that are based on population of individuals. Each individual represents a search point in the space of potential solutions to a given problem and imitates nature principles to create optimization procedures.
Table 1 presents the DE scheme for the involved variables behavior.

Table 1. Behavior schemes of the variables involved in the Differential Evolution Method

Process of forming a vector / Mutant in the solution space	Mutation schemes generated
	**Mutation:** $v_{i,G+1} = x_{r1,G} + F(x_{r2,G} - x_{r3,G})$ **Individual Reference:** $x_{r1,G}$ ↓ **Mutation:** $v_{i,G+1} = x_{mutant} + F(x_{r2,G} - x_{r3,G})$ **Individual Reference:** x_{mutant} ↓
	**Mutation:** $v_{i,G+1} = x_{r1,G} +$ $+F(x_{mutant} - x_{r3,G}) + F(x_{r2,G} - x_{r3,G})$ **Individual Reference:** $x_{r1,G}$

The classic Differential Evolution has four main phases: initialization, mutation based on vector difference, crossing / recombination and selection. The algorithm is controlled by three parameters:

- I_NP is the size of the population i, and the number of competing solutions in a given generation G (I_itermax = maximum number of iterations or generations). It can also be called the population vectors number. This population size is directly proportional to I_D, which is the number of parameters of the objective function, or even of variables involved or even dimensionality of the problem. The I_D value is 10 times to obtain indicated I_NP;
- F is the factor constant scale or weighting, typically between 0 and 2, that controls the differential mutation of the process (or also called the step size of differential evolution). It is the pass rate, which defines the probability of a survive test vector;
- F_CR is the crossover rate specified in the interval between 0 and 1 (or also called a crossover probability constant). The higher this rate, the more likely the candidate vector components are equal to the mutant vector components.

In Sobrinho *et. al* (2020) [5], for a beam element, though the following Eq. (1), the stiffness matrix establishes how the physical and material properties are stored and also how each beam is modified to incorporate the variable damage.

$$[K_j] = \frac{E(1-[d_i])}{l^3}\begin{bmatrix} Al^2 & 0 & 0 & -Al^2 & 0 & 0 \\ 0 & 12I & 6Il & 0 & -12I & 6Il \\ 0 & 6Il & 4Il^2 & 0 & -6Il & 2Il^2 \\ -Al^2 & 0 & 0 & Al^2 & 0 & 0 \\ 0 & -12I & -6Il & 0 & 12I & -6Il \\ 0 & 6Il & 2Il^2 & 0 & -6Il & 4Il^2 \end{bmatrix}_{6x6}, \quad (1)$$

where [di] is the variable design vector and, the variable design vectors “di” shown in Eq. (1), could assume values between 0 (intact element) and 1 (damaged element).

3 Numerical and Experimental Static Analysis: Two Simply Supported Intact Steel Beam

In this case of two simply supported intact steel beam (VR), with load in the span middle, as represented in Fig. 2, from the Silva (2015) work.

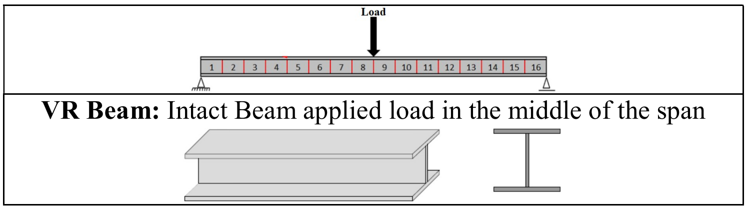


Figure 2. Intact steel beam (VR) for static analysis (Silva, 2015 [6])

The intact condition shall be used as a parameter for checking the static damaged condition of case 1 (VD1-2), case 2 (VD1-4) and case 3 (VD2-2) beams, all with a loading order around 3 kN.

3.1 Numerical and Experimental Static Analysis Case 1: Two Simply Supported Steel Beam (VD1-2)

The damaged two simply supported steel beam (Case 1: VD1-2), with load in the span middle, can be seen in Fig. 3 below.

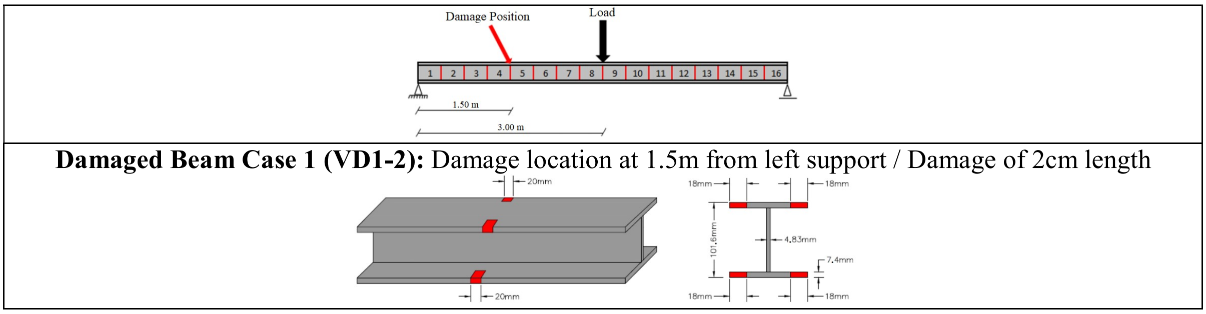


Figure 3. Damaged steel beam: Case 1 VD1-2 (Silva, 2015 [6])

The intact and damaged graphic analyses corresponding to the beam case 1 displacements, presented in Fig. 4, where: the x-axis corresponds to the 6.00 m length of the beam and the y-axis corresponds the displacements generated by the loads application, in the case being used loads of 3 kN approximately.

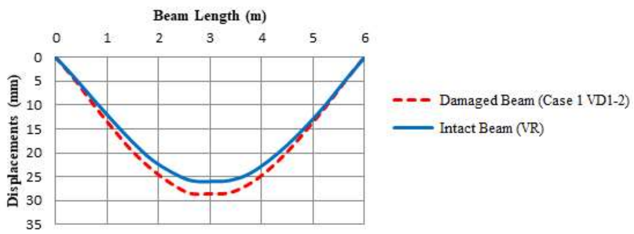


Figure 4. Intact and damaged graphical analysis corresponding to the displacements for the beam of case 1 (load 3 kN approximately)

The simulations proposed in this approach concern the results of the values obtained in the essentially experimental analysis used to identify the structure damaged elements. Due to the reasonable computational processing time, 100 iterations were defined for this experimental analysis. In this analysis, only the values of intact and damaged static displacements of the beam elements were considered. Figure 5 shows the result of the problem solution.

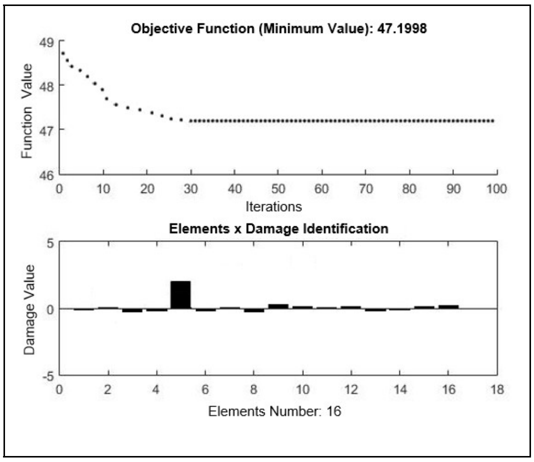


Figure 5. Damaged identification VR ↔ VD1-2 (100 iterations): Beam load Case 1 (case of damage from left support – 1,5m=L/4)

3.2 Numerical and Experimental Static Analysis Case 2: Two Simply Supported Steel Beam (VD1-4)

The damaged two simply supported steel beam (Case 2: VD1-4), with load in the span middle, and damage configuration as represented in Fig. 6, from the work of Silva (2015) [6].

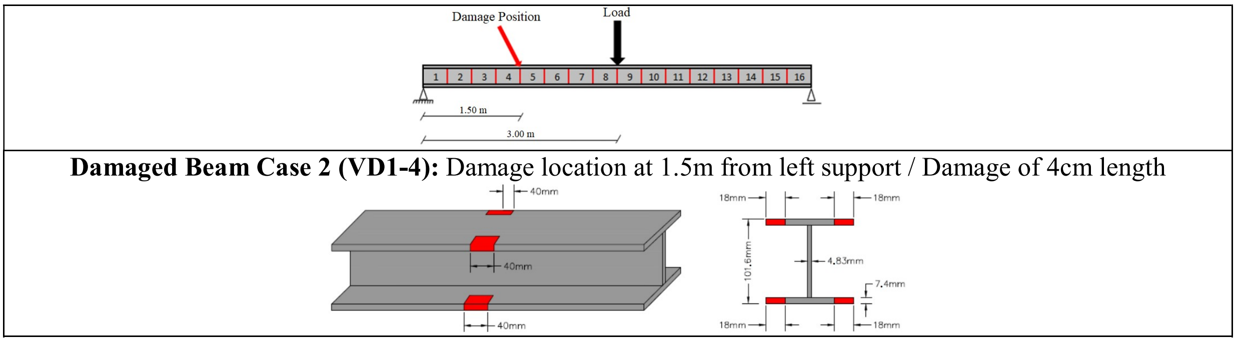


Figure 6. Damaged steel beam: Case 2 VD1-4 (Silva, 2015 [6])

The intact and damaged graphic analyses corresponding to the beam case 2 displacements, presented in Fig. 7, where: the x-axis corresponds to the 6.00 m length of the beam and the y-axis corresponds the displacements generated by the loads application, in the case being used loads of 3 kN approximately.

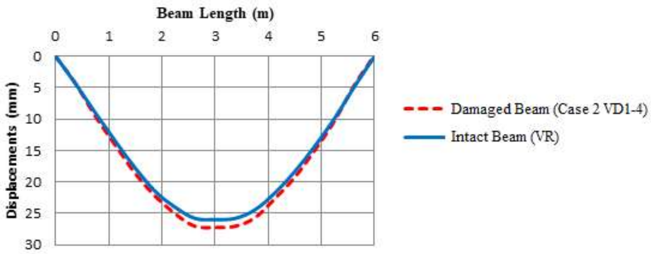


Figure 7. Intact and damaged graphical analysis corresponding to the displacements for the beam of case 2 (load approximately 3 kN)

The simulations proposed in this approach concern the results of the values obtained in the essentially experimental analysis used to identify the structure damaged elements. Due to the reasonable computational processing time, 100 iterations were defined for this experimental analysis. In this analysis, only the values of intact and damaged static displacements of the beam elements were considered. Figure 8 shows the result of the problem solution.

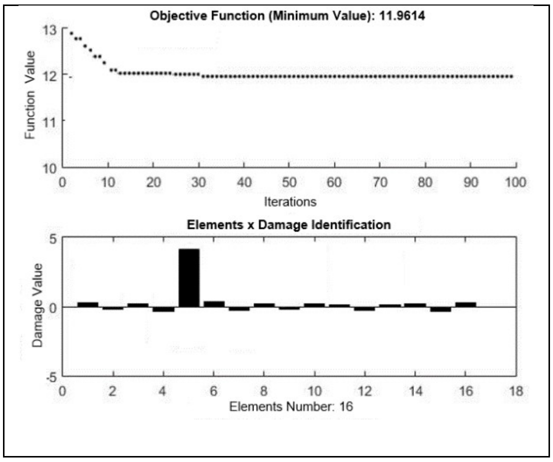
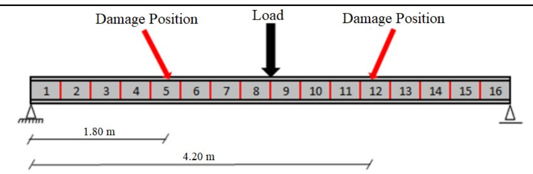


Figure 8. Damaged identification VR ↔ VD1-4 (100 iterations): Beam load approximately 3 kN Case 2 (case of damage from left support – 1,5m=L/4)

3.3 Numerical and Experimental Static Analysis Case 3: Two Simply Supported Steel Beam (VD2-2)

The damaged two simply supported steel beam (Case 3: VD2-2), from the work of Silva (2015) [6], with damage configuration and load in the span middle, can be seen in Fig. 9 below.



Damaged Beam Case 3 (VD2-2): Damage location at 1.8m and 4.2m from left support / Damages of 2cm length

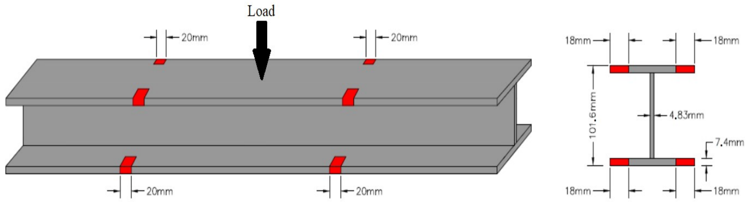


Figure 9. Damaged steel beam: Case 3 VD2-2 (Silva, 2015 [6])

The intact and damaged graphic analyses corresponding to the beam case 3 displacements, presented in Fig. 10, where: the x-axis corresponds to the 6.00 m length of the beam and the y-axis corresponds the displacements generated by the loads application, in the case being used loads of 3 kN approximately.

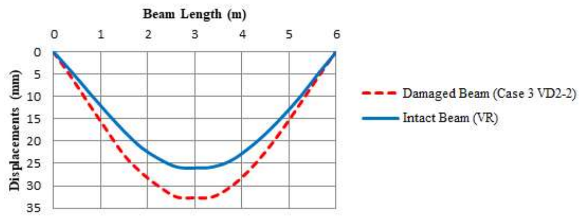


Figure 10. Intact and damaged graphical analysis corresponding to the displacements for the beam of case 3 (load approximately 3 kN)

The simulations proposed in this approach concern the results of the values obtained in the essentially experimental analysis used to identify the structure damaged elements. Due to the reasonable computational processing time, 100 iterations were defined for this experimental analysis. In this analysis, only the values of intact and damaged static displacements of the beam elements were considered. Figure 11 shows the result of the problem solution.

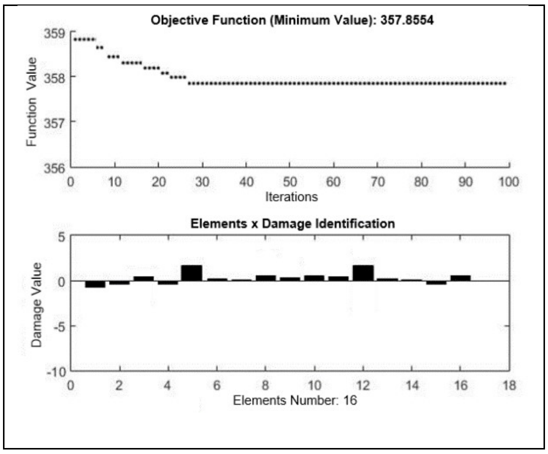


Figure 11. Damaged identification VR ↔ VD2-2 (100 iterations): Beam load approximately 3 kN Case 3 (case of damage from left support – 1.8m and 4.2m)

4 Conclusions

The structural responses of beams, under different loading conditions, were used through their static displacements to identify damage. The damage is considered through the rigidity properties alteration (decreasing) of these elements. These are studies derived from the Inverse Problem Methods or Systems Identification Methods.
The summary obtained results can be seen in Tab. 2 below.

Table 2. Summary: Steel Beams Cases 1, 2 and 3

Item	Beam (Cases)	Loads (kN)	Analysis	Damage Cases	Iterations	Damaged Elem. Pos.	Damage %	Obj. Func. Min.
VD1-2	Two simply supported Beams (Cases 1, 2 and 3)	≅ 3kN	Experim.	from 1.5m = (L/4)	100[a]	4	≅ 2%	47.1998
VD1-4		≅ 3kN		from 1.5m = (L/4)	100[a]	4	≅ 4%	11.9614
VD2-2		≅ 3kN		from 1.8m and 4.2 m	100[a]	5 and 12	≅ 2%	357.8554

With these objective functions minimum values found in the hundredth iteration and with the elements damage values following in accordance with the proposed problem, find damage of approximately 2% in element 4 for the analyses with the case 1 beam VD1-2 and 4% in element 4 for the analyses with the case 2 beam VD1-4, and some disturbances damage identification for the other elements.
On the other hand, the objective functions minimum values found in the hundredth iteration, a number of damages of 2% in the elements 5 and 12 for the VD2-2 case 3 beam, with the elements damage values following in accordance with the proposed problem, in addition to some minor disturbances for the other elements, mainly near the supports.
Near the damage points there were some distortions probably because of the disturbance damage identification caused, where for a more realistic model adequacy, a larger number of iterations could be used.
The damage identification analyses in this examples were restricted to the displacements obtained in the intact and damaged experimental analyses, but as previously reported, a greater number of iterations were again used which allowed a decrease in the waste generated, even where there were large differences in displacements, the presence of point loads, near the two simply supports or even close to the damaged regions, despite this elements damage values follow in accordance with the proposed problem. It is stressed here that increasing the number of iterations, in some cases, helps to solve the problem of approaching a local minimum.
With the analysis of these beams, it can also be affirmed that a greater number of displacement information would also help the work of the optimizer. Even so, the tool met the ability to locate and quantify damage in any element of the structures under study.

Acknowledgements. The Authors thank the Graduate Program in Structural Engineering and Civil Construction of the Department of Civil and Environmental Engineering at the University of Brasilia, Brazil.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] X. S. Yang, G. Bekda and Nigdeli S. M.. *Metaheuristics and Optimization in Civil Engineering*. Springer International Publishing. DOI: 10.1007/978-3-319-26245-1, 2016.
[2] G. Gomes, A. Portela, B. E. Sobrinho and I. Lustosa, *Analysis of Dual Boundary Element in Shape Optimization*. IOSR Journal of Mechanical and Civil Engineering, v. 13, p. 127-141 e ISSN: 2278-1684, p-ISSN: 2320-334X. DOI: 10.9790/1684-130304127141, 2016.
[3] Y. I1. Choi, *Damage Identification Techniques for Bridges Using Static Response*. Tese de Doutorado, Hanyang University, Seoul, 153p., 2002.
[4] R. Storn, K. Price, *Differential Evolution – A Simple and Efficient Heuristic for Global Optimization over Continuous Space*s. Journal of Global Optimization, v. 11, p-341-359, 1995.
[5] B. E. Sobrinho, G. Gomes, W. V. Silva, R. Silva, L. Bezerra, E. Palechor, *Differential Evolution Algorithm for Identification of Structural Damage in Steel Beams*, Frattura ed Integrità Strutturale, 52 (2020) 51-66. DOI: 10.3221/IGF-ESIS.52.05, 2020.
[6] R. S. Y. R. C. Silva, *Monitoring and Identification Numerical and Experimental of Damages in Steel and Concrete Beams and Bridges Using Wavelet Transforms*. Tese de Doutorado em Estruturas e Construção Civil. Publicação E.TD-001A/15, Departamento de Engenharia Civil e Ambiental, Universidade de Brasília, Brasília, DF, 237 p. (Doctoral thesis), 2015.