A new multi-span arch bridge over the Piave River in Venice: conceptual design and structural optimization

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ABSTRACT: Not infrequently, building yards of important infrastructures take remarkably long time to be accomplished and are characterized by several interruptions and resumptions. This is the case of the bridge over the Piave river in San Donà, an outstanding 500m arch structure on five bays of 100m each, located in a strategic area just outside the city of Venice-Italy. The interruption of the construction works was, for the case mentioned, contemporary to the introduction of a new regulation, the O.C.P.M. n 3274, concerning seismic design and seismic classification of the National territory. This fact, since the original project was characterized by a massive box girder concrete deck on pile foundations (thus not conceived for horizontal loads at first), gave rise to the necessity of starting with an updated design aiming to achieve a much lighter composite steel and concrete box girder deck. The new deck was connected to the already built piers by means of non conventional steel-to-concrete connections ensuring hogging moment resistance at supports, and it is characterized by a sophisticated aesthetics and by an optimized distribution of structural material obtained through an iterative design-and-check process. In the following paper, the structural optimization process aiming to reduce the weight of the superstructure of the bridge will be presented. This study follows a previous one based on a manual ESO (evolutionary structural optimization) performed into a FEM model (Zordan T. et al. 2010), for which all computer automatic procedures were been replaced by a step-by-step iterative process controlled by the designer. Now this results are compared to the ones coming from a totally automatic ESO procedure performed with Ansys V.12 software, and a semi-automatic procedure, that use Ansys topological optimization's results for identifying shape finally defined by the user himself.

1 CASE STUDY

The project taken into consideration is the newly built San Donà Bridge over Piave river which original project, from Prof. Enzo Siviero, was characterized by a five arch pre-stressed concrete structure over a total length of 500m arranged on 5 bays of 100m each (Fig.1).

The cross section of the original project, with a total width of 17.86m, as presented in Fig.3 was conceived with cast-in-place concrete, poured on prefabricated arched concrete segments supported by provisional scaffolding.

The construction of the bridge was slowed by the raise of financial problems and the building yard had to deal with interruptions and resumptions. During this period some unforeseen event, not taken into account in the initial project occurred.

First of all the publication of the new Italian seismic code O.C.P.M. n 3274 brought to the definition of new seismic classification of the National territory; in particular the site under consideration was defined as seismic zone 3, which means low seismic hazard (base acceleration equal to 0.15g). Due to the fact that the structure was dimensioned without taking into account any horizontal seismic action, its foundations, already built, became inappropriate for this new seismic specification, requiring an increment of about 35% in resistance capacity.

Furthermore, the Venice Water Authority, responsible for the management of the river spanned by the bridge, declared that erection phases without any provisional supports and scaffolding resting on the riverbed, as foreseen in the original project, should be preferred.

For this reason a simple foundation retrofitting was not sufficient and a global review of the project has been performed.

It is necessary to underline that at the moment of the project updating, part of the piers and the abutments had already been built, as shown in Fig.1 and 2.

Hence, considering that the concrete piers represented a remarkable part of the overall mass of the bridge, a significant reduction of the superstructure weight was a required goal in order to comply with the new seismic prescriptions.

These constraints gave the occasion for a thorough review of the former solution with a completely new layout for the deck: a suitable option was found in a composite steel concrete deck because of its lightness, acceptable costs, favourable construction phases on the spans considered and possibility to re-create the shape of the former pre-stressed cross section, as required by the Landscape Authority. The comparison between the cross section of the bridge, prior and after re-design, is presented in Fig.4.

The new deck was connected to the already built piers by means of non conventional steel-to-concrete connections ensuring negative moment resistance at supports.

The needing of achieving the lightest solution possible suggested to perform an optimization process on the bottom flange, in order to reduce the total steel weight; at the moment of bridge retrofitting a manual step by step ESO procedure was performed (Zordan T. et al. 2010). In the following such results are compared to solutions obtained through specific softwares, like the Ansys V.11 topologic optimization and design variable optimization tool.

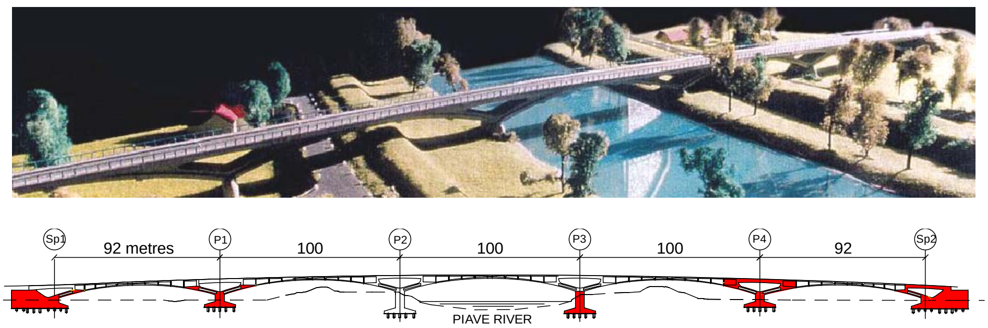


Figure 1 : The original solution as planned and as built (in red hatch) before work interruption

Figure 2 : Some of the parts of the bridge built before the introduction of the new seismic regulation

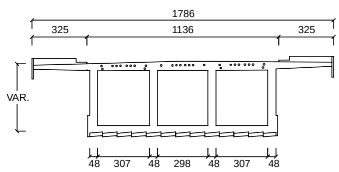


Figure 3 : Typical cross section of original solution

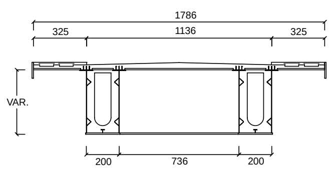


Figure 4 : Typical cross section of updated solution

2 FEM MODEL

The whole optimization process has been performed on a parametric 3D Finite Element Model of the considered bridge built in Ansys V11 (Fig.2).

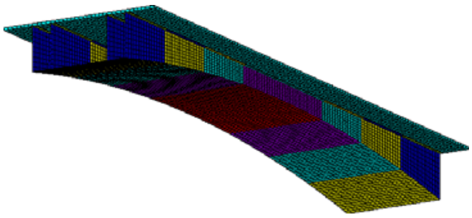


Figure 5 : 3D parametric FEM

Table 1 : nodes and elements number in FE model

Nodes	Elements				
	deck	top	web	bottom	total
37406	4320	960	4320	2640	12240

The element type SHELL93 was used for the concrete deck and steel plates. The total numbers of nodes and elements of the starting model were listed in Table 1.

Both the ends of bridge model are fixed. The full shear connections were provided between concrete deck and steel girder.

Besides all the dead loads of bridge, the following ones were considered according to Italian Regulations: full span pedestrian crowd (4kN/m^2) and 3 lanes loads (30kN/m uniform distributed load plus 3x200kN concentrated tandem load, considered in 5 different positions: 0, ¼, ½, ¾ and 1 of the span length)

3 OPTMIZATION PROCESS

3.1 Design Variable Optimization Process (D.V.O.P.): initial flanges' thicknesses choice

The research of the lightest solution as possible started from the research of the combination of thicknesses of the steel plate, able to grantee the less steel volume, limiting at the same time the maximum stress. For this process the Design Variable Optimization Process (D.V.O.P.) in Ansys V.11 was used. The adopted procedure was a first order method, which uses gradients of the dependent variable (total steel's volume) with respect to the design variables (steel plates' thicknesses). For each iteration, gradient calculations (which employ a conjugate direction method) are performed in order to determine a search direction, and a line search strategy is adopted to minimize the problem. Thus, each iteration is composed of a number of sub-iterations that include search direction and gradient computations.

Constraints are imposed on the maximum allowable stress for consider a given designs et as feasible. The optimization process adopted converts the problem to an unconstrained one by adding penalty functions to the objective function. Considering a used steel of quality S355, the maximum allowable stress at ULS is equal to 335 MPa, which as been limited to 285 MPa for this initial optimization process (85% of max allowable stress).

In Table 2 from the whole identified design set, only the feasible ones are reported; the best one resulted to be n 25, from which the initial steel thicknesses distribution was chosen.

3.2 Manual optimization process (M.O.P)

The manual optimization process was the original process used for identifying the best shape of bottom flange for the considered bridge at moment of its retrofitting. The basic idea was that of removing unexploited material on the base of an ESO procedure. The fact of performing the optimization in a way totally controlled by the designer allowed for removing ellipse shaped holes from less stressed area of the bottom flange. This step-by-step kind of "design and check" had the objective was that of achieving a relatively handy mean for attaining the final optimum deck configuration with the support of numerical results. The finally optimum shape obtained represented a desirable and innovative layout with reference to the bridge aesthetics where the flow of forces is emphasized by the geometry of the superstructure and structural issues can be considered complementary to architectural needs, as required by the fundamentals of Structural Architecture discipline

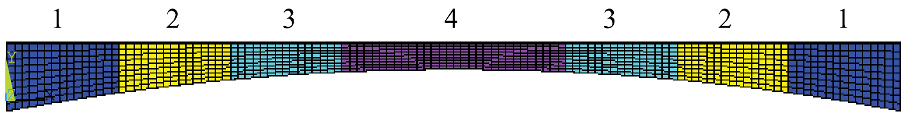


Figure 6 : Identification of different optimization “groups” for the considered bridge

Table 2 : Steel flanges’ thicknesses identification from Design Variable Optimization Process

Set no.	2	5	6	8	9	10	12	17	19	23	25*	chosen
σ_{MAX} (MPa)	211.3	231.5	253.0	276.2	276.7	184.5	249.4	263.5	279.1	283.3	278.7	280.2
Volu. (m^3)	27.2	23.8	26.5	28.0	25.6	30.2	29.1	21.2	20.6	20.1	19.4	19.2
TOP_1	19.4	21.0	15.3	20.1	15.9	28.2	27.6	18.8	15.9	15.9	14.6	15
TOP_2	16.4	10.7	28.1	18.3	10.8	29.4	24.5	10.6	10.5	10.4	10.2	10
TOP_3	25.9	11.0	16.2	22.3	26.0	15.6	16.0	10.7	10.6	10.4	10.3	10
TOP_4	21.6	22.7	19.7	20.7	12.7	13.2	28.2	18.1	16.6	15.4	14.5	15
WEB_1	15.4	13.8	10.1	18.8	16.3	18.8	15.1	13.1	12.4	11.7	11.7	12
WEB_2	16.2	10.6	16.3	16.0	15.5	18.5	10.3	10.5	10.5	10.3	10.3	10
WEB_3	18.5	10.2	15.0	12.2	12.8	16.6	11.5	10.2	10.1	10.1	10.1	10
WEB_4	10.0	14.7	11.4	16.9	14.6	14.0	17.0	13.8	13.2	12.2	11.6	12
BOT_1	26.9	25.5	24.3	21.8	21.3	29.6	24.0	22.4	21.6	21.6	21.7	22
BOT_2	19.1	24.1	18.0	13.3	24.3	28.4	29.7	18.9	18.9	18.7	16.5	16
BOT_3	17.8	11.9	25.0	29.6	26.4	10.7	28.4	11.5	11.0	11.0	10.9	10
BOT_4	23.8	21.6	27.3	24.7	12.0	28.6	22.1	17.9	17.9	17.7	16.5	16

*Note: BOT = bottom flange; WEB = web plates; TOP = top flange; numbers (1,2,3,4) refer to identified thicknesses’ groups in
Figure ; dimension are in mm.

Figure 7 : Final bridge’s optimized layout

3.3 Topological optimization process (T.O.P)

Topological optimization is used to find a special form of a structure and to define, through the use of finite element methods, its closest shape and material distribution with reference to a selected goal, so that an objective criterion (i.e., global stiffness, natural frequency, etc.) attains a maximum or minimum value under given constraints (i.e., volume reduction…) .

Unlike traditional optimization, topological optimization does not require the explicit definition of optimization parameters (i.e., independent variables to be optimized). In topological optimization, the material distribution function over a body serves as optimization parameter. The theory of topological optimization seeks to minimize or maximize the objective function subject to the constraints defined. The design variables are internal, pseudo-densities (η_i) that are assigned to each finite element (i) in the topological problem. The pseudo-density for each element varies from 0 to 1; where $\eta_i \approx 0$ represents material to be removed; and $\eta_i \approx 1$ represents material that should be kept.

In the case of "maximum static stiffness design" subject to a volume constraint, which sometimes is referred to as the standard formulation of the layout problem, the goal is to minimize the energy of the structural static compliance for a given load case subject to a given volume reduction. Minimizing the compliance is equivalent to maximizing the global structural static stiffness.

Using like starting point thicknesses distribution obtained from D.V.O.P., the internal part of the bottom flange comprises between the two box girders is subject to T.O.P. fixing different percentage of volume reduction (V.R.), from 0 to 100%. Results of T.O.P. in term of pseudo-densities for different V.R. percentage are reported in Table 6 (left column); the results of such optimization process is compared with previous M.O.P.

3.4 Design optimization process (D.O.P) from T.O.P. results

A further optimization process has been used for identification of best structure layout. It try to take the best from M.O.P. and T.O.P together. It means that starting from the results from the topological optimization, the irregular holes found out with such procedure are regularized through ellipse shaped holes.

The adopted shape identification process is reported in Table 6 (right column): through a grid, the dimension and centre position of different ellipse can be easily estimated and used for updating Finite Element model. This procedure allows the design still to actively control the optimization process, even if the main procedure is fully automate by the software.

3.5 Summary of optimization results

In following pages the results obtained from different O.P. are compared. In Table 3, Table 4 and Table 5 the different identified models are reported; T stays for T.O.P, D stays for D.O.P. and M stays for M.O.P.. Obtained results are reported in term of stress contour (Table 7) and graphics reporting the percentage increment of vertical displacement in the deck (Table 9) and stress percentage increment with reference to the initial full bottom flange model (Table 8). In this last table are compared both the maximum Von Mises stresses and the averaged one above the different finite elements. The furnish the maximum number of information, results are reported separately for what concern the top flange, the web, the bottom flange and the whole steel plates.

At the end a specific Optimization Index (O.I) has been defined, through which identify the best solution. A suitable one has been recognized on the following (which represent a slightly modified index with respect to the one used at time of retrofitting):

$$\text{O.I.}\ (X,i) = \left(\frac{V_i - V_0}{V_{real} - V_0} - \frac{X_i - X_0}{X_{real} - X_0} \right) \cdot \beta \tag{1}$$

Where V stay for volume, the subscript i, 0 and "*real*" stay respectively for i-th model, initial model and real bridge model (model M7 from M.O.P. in Table 7); X stays for the considered parameter, that could be Von Mises stresses σ or displacements p. β is just a normalization factor (put O.I corresponding to 100% V.R. equal to 1 in module). At the end to have a global optimization index (G.O.I), that takes into account both stresses and maximum displacements of the bridge, the O.I.(σ,i) and O.I.(d,i) have been averaged. Of course the higher is the G.O.I, the most convenient is a certain model's i solution.

$$\text{G.O.I.}\ (i) = (\text{O.I.}\ (\text{s},i)\ +\ \text{O.I.}\ (\text{d},i))/2 \tag{2}$$

Table 3 : T.O.P. models

Model	V.R. %
T0	0
T1	15.4
T2	21.9
T3	27.8
T4	32.1
T5	35.6
T6	45.7
T7	51.6
T8	62.1
T9	70.5
T10	81.7
T11	89.0
T12	100.0

Table 4 : D.O.P. models

Model	V.R. %	X0 m	AX m	BY m
D0	0.0	-	0	0
D1	16.3	17.5	6.5	2
D2	24.5	18	9	2
D3	34.5	17	10	2.5
D4	48.5	19	12	2.5
D5	42.5	15	12.5	2.5
D6	58.5	19	17	2.5
D7	59.3	17.5	16.5	2.5
D8	64.2	17.5	17.5	2.5
D9	76.2	16.5	18.5	2.8
D10	84.7	18	23	3.1
D11	87.8	30	41	3.1
D12	100	30	∞	3.1

Table 5 : M.O.P. models

Model	V.R. %	X0 m	AX m	BY m
M0	0.0	-	0	0
M1	6.8	17.5	6.5	2
M2	15.4	18	9	2
M3	29.2	17	10	2.5
M4	48.5	19	12	2.5
M5	58.2	15	12.5	2.5
M6	64.0	19	17	2.5
M7	75.2	17.5	16.5	2.5
M8	85.3	17.5	17.5	2.5
M9	100.0	16.5	18.5	2.8

*Note: V.R.= volume reduction; X0= ellipse center position; AX= major ellipse's axis; BY= minor ellipse's axis

Table 6 : Pseudo-densities from T.O.P. and identification of optimized shape in D.O.P.

V.R.% topo	Topological optimization process	Design optimization from topological results	V.R.% design
10.0			16.3
20.0			24.5
30.0			34.5
30.0			48.5
40.0			42.5
40.0			58.5
50.0			59.3
60.0			64.2
70.0			76.2
80.0			84.7
90.0			87.8

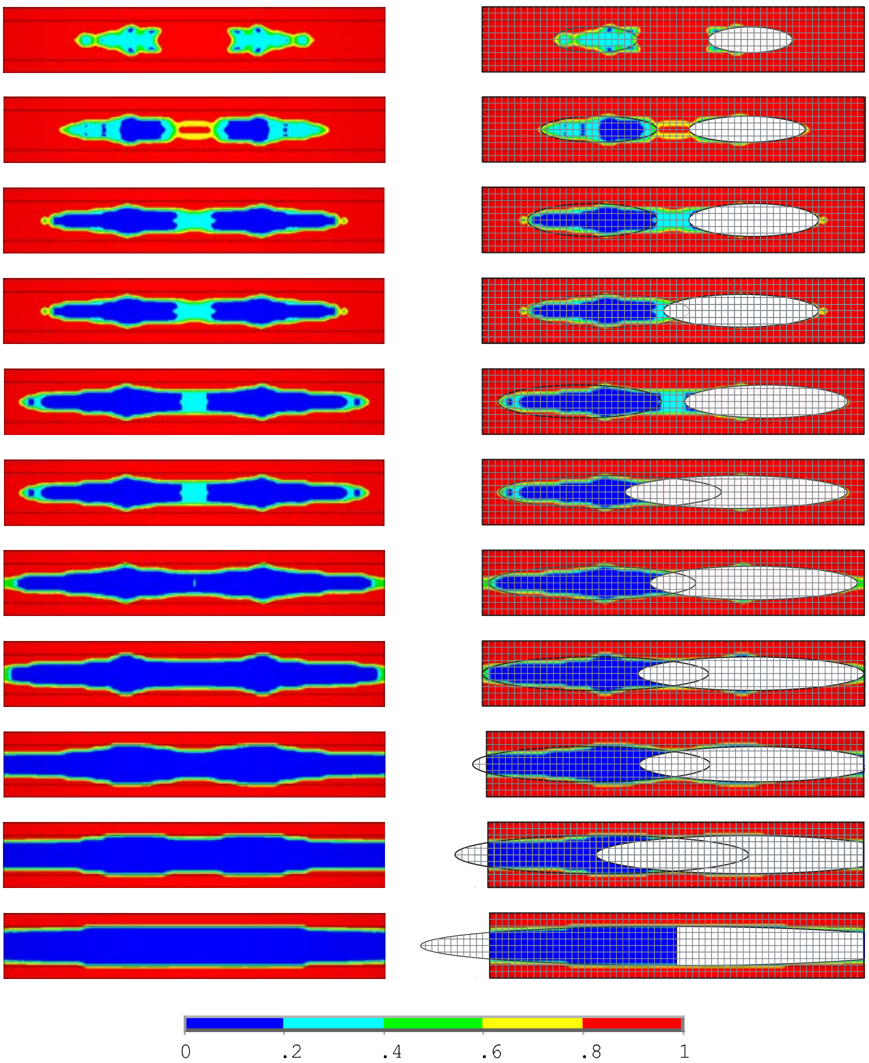
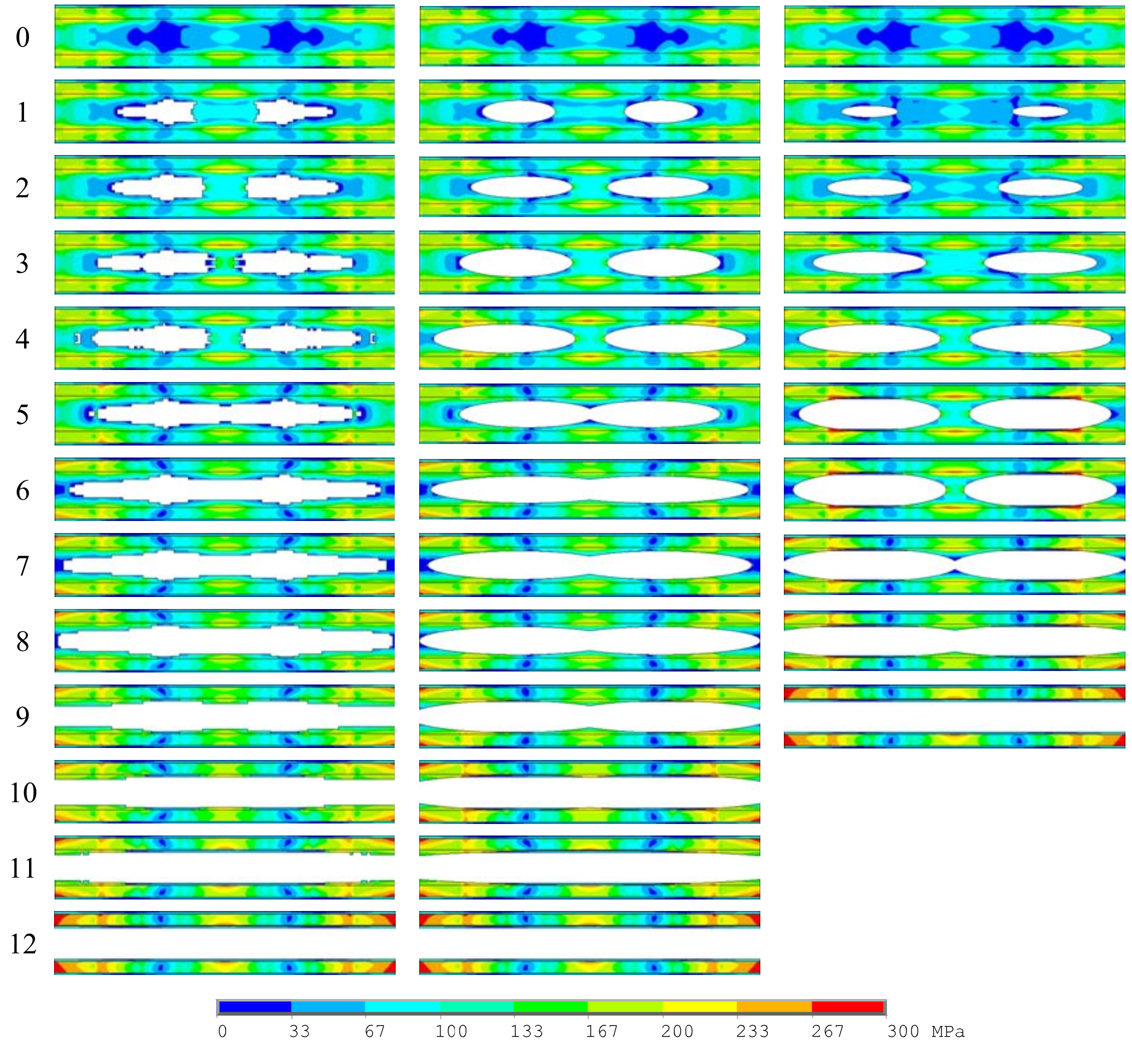


Table 7 : Stress results from different optimization processes

No. T.O.P. D.O.P. M.O.P.



4 ANALISYS RESULTS AND CONCLUSIONS

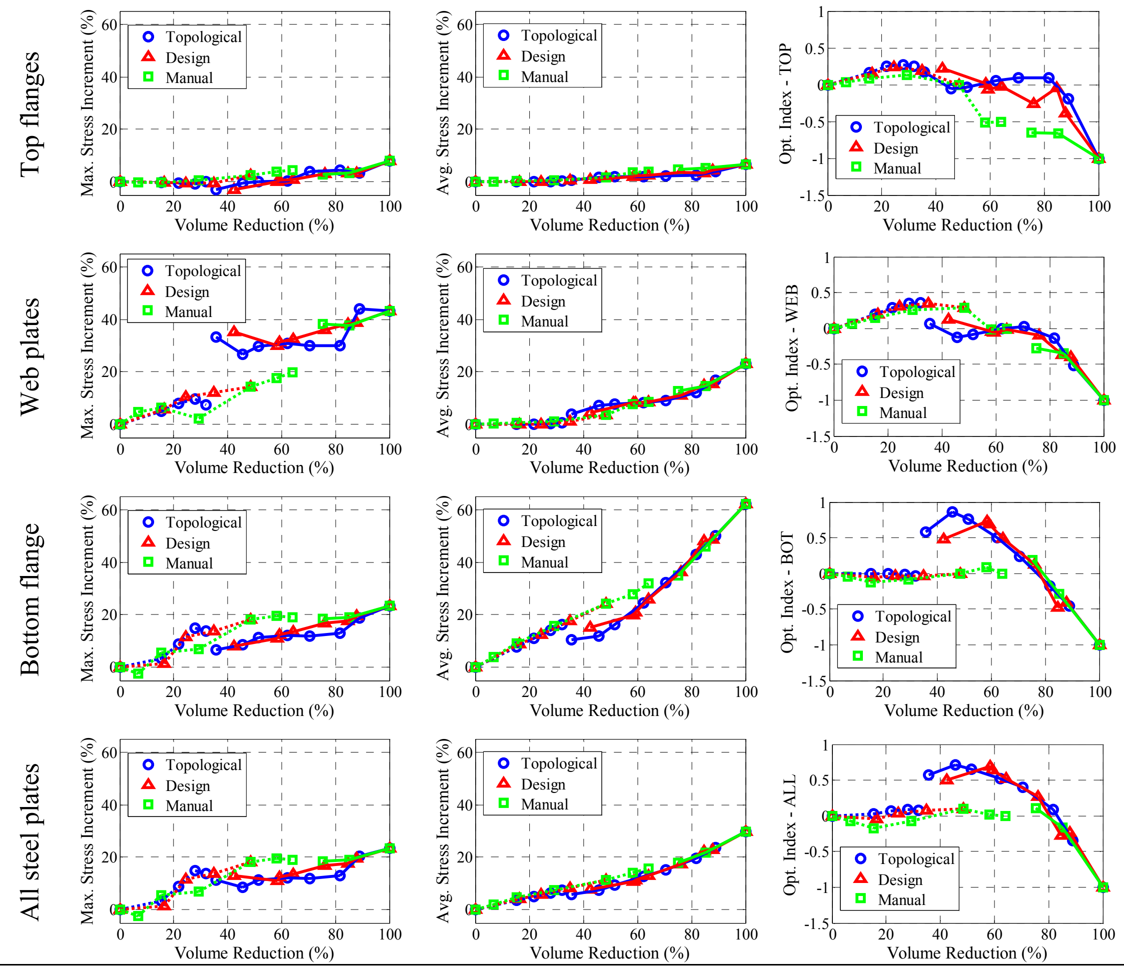
From previous graphics it is possible to get a general idea of the effect produced by holes with increasing dimensions, located where the steel bottom flange of the superstructure turns out to be subjected to lower stress levels. First of all is possible to notice how the three compared optimization methods presented in this paper, namely M.O.P. , D.O.P and T.O.P, have similar trends for what concerns stresses, displacement and related O.I..

In general two different main conditions can be identified from the graphics: bridge characterized by two separate holes, and a single hole. As soon as the holes become big enough to melt in a single larger one it can be noticed a decrease in the stress rate in the bottom flanges but an increase in the webs, which can be considered an unfavorable condition for bucking phenomena. More remarkable differences can be noticed in the displacement's graphics: a sort of structure relaxation it can be recognized as soon as the central part of the bottom flange is removed and the two holes become a single one, characterized by a displacement increment bigger than 35%. This behavior and the fact that a bigger increment in the volume reduction tends to produce a higher rate in the stress increment, make the G.O.I become unfavorable for bridge's layout characterized by one single big hole (G.O.I is negative).

For what concerns the layout with two separate holes, it is not easy to clearly identify the optimum design. The higher O.I. is relative to model M4, slightly different from model M7, which is layout of the real bridge. However, it is to notice that the difference in the O.I. is very limited and furthermore it grantees a saving of the initial bottom flange volume nearly equal to 75.2% (model M4 is equal to 48.5%). This reduction granted a saving of 4.51m^3 of steel, which correspond to 23% of the initial total steel volume. Finally, it must be noticed how the adopted solution has been found out only through the M.O.P: that means that the automatic procedure it's just suitable to address the designer to the final solution, whereas his sensibility and engineering judgment still plays a key-role for the final choice.

Table 8 : Stress increment comparison (%) & O.I(σ) vs. V.R.

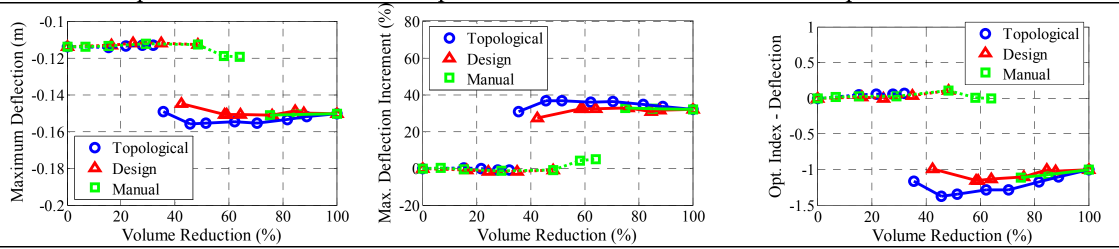
Max. stress increment % | Avarage stress increment % | Optimization Index



*Note: dashed line = two disconnected holes; solid line = two interconnected holes or unique hole

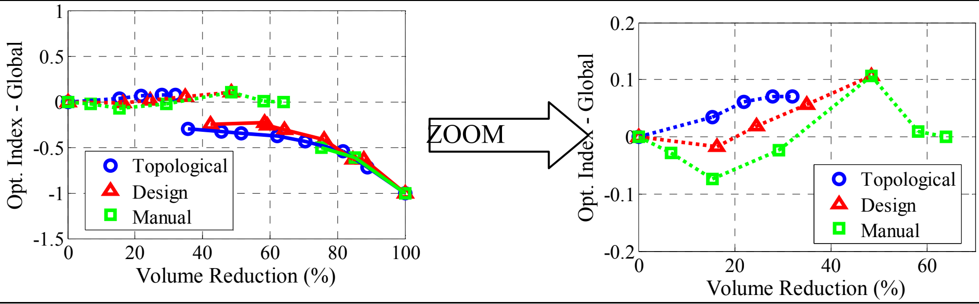
Table 9 : displacement increment comparison & O.I.(d) vs. V.R.

Displacement | displacement increment % | Optimization Index



*Note: dashed line = two disconnected holes; solid line = two interconnected holes or unique hole

Table 10: Global Optimization Index (G.O.I.) vs. V.R.



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REFERENCE

Zordan T., Briseghella B. and Mazzarolo E., 2010. Bridge Structural Optimization Through Step-by-Step Evolutionary Process, SEI Journal 20(1), p.72-78.