

DESIGN OPTIMIZATION OF LATTICE GIRDERS ACCORDING TO MEMBER AND JOINT-RELATED DESIGN CONSTRAINTS

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ABSTRACT

This study concerns with the design optimization of geometrically nonlinear lattice girders. The novelty of this study comes from simultaneously using the member and joint related design constraints, which are borrowed from the provisions of API RP2A-LRFD specification and defined depending on both member and joint strengths. A multi-objective design optimization approach named ImpNSGAIL, which was improved in way of integrating both a neural network implementation and an automatic generating lattice girder tool for the search mechanism of NSGAIL, is utilized in this study. Hence, this study purposes to investigate how to vary the optimality quality depending on the presence of joint strength-related design constraints. Thus, it is demonstrated that the presence of the joint strength-related design constraints causes to a divergence in the construction cost of optimal designs. Consequently, it is proved that the ImpNSGAIL has a higher capability of exploring a conceptual lattice girder configuration in order to obtain an optimal design satisfying the economy, load-resistance and serviceability-related design conditions at the same time.

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1. Introduction

The steel lattice girders, members of which are connected to each other making use of a welding process, bolts and etc., are widely utilized in the structural engineering field (for example roofs, bridge, industrial applications etc.) [1]. In order to both increase its manufacturing accuracy and decrease its construction cost; they are preferably constructed in a manufacturing fabric of steel structures using a number of robots for the welding process [2]. Therefore, the effect of excessive welding process on the joint strength has to be considered in the design phase of lattice girder. Hence, the complexity in the design of lattice girders with respect to the generational design approach is correspondingly increased. Moreover, an increased demand to the cost-saving design of lattice girder causes to emerge the additional design complexities. In fact, these design complexities, which are exhaustively tackled in this section, constitutes the fundamentals of ImpNSGAIL.

A generational design approach is also utilized in the design of steel lattice girders. It begins by deciding a certain geometric and topologic configuration of lattice girder since the various conceptual models such as Warren, Pratt and etc. has been successfully utilized to represent its framing configuration [3-4]. Following the decision on the conceptual model of lattice girder, its member cross-sectional properties are determined. Then, the sizes of lattice girder members are determined according to a database, which contains the cross-sectional properties of steel profiles. For this purpose, the member responses are computed using a linear structural analysis method. However, when the deformation in the geometrical shape of lattice girder is large, the structural responses are not correctly computed. Because, the large deformations of joints cause to arise the additional responses in the lattice girder members. Therefore, an appropriate approach is the usage of a non-linear structural analysis method for the computation of the member and joint responses. [5-8]. Following the computation of member responses, the capacities of member strengths is checked according to an available national or international design code [9]. Therefore, the designer's experience has a big importance in this stage in order to reduce the number of trials.

This generational design procedure has still been applied to determine the most suitable construction of lattice girder. However, the best way for the exploration of a cost-effective lattice girder design in a lower trial number is the inclusion of an optimization process into the design procedure [10-11].

In the optimal design of steel structures, the economy is provided in a way of arranging the cross-sectional properties of its members for a lower weight of steel structures. In this generational sizing optimization procedure, the member cross-sectional properties are determined by checking the member stress and joint displacement values according to their pre-specified upper values [12]. Although there is a big variety in the steel profiles with different cross-sectional shapes and properties, the circular-hollow-shaped cross-sections are preferably utilized to represent the size type design variables. Because, their torsional strengths are higher than those with open cross-sections [13-16]. It was shown

that an execution of this generational sizing optimization procedure causes to decrease the number of feasible solutions [17]. Furthermore, it was also demonstrated that involving the shape and geometry of lattice girder into the optimal design procedure leads to the exploration of optimal design with higher economic, serviceability and load-resistance capability. Particularly, it was also shown that the stability capacity of steel structure was increased through the various arrangements in its current geometrical form [18]. Therefore, using a conceptual model for the representation of lattice girder framing configurations provides a big advantage in introducing the shape and geometric properties of lattice girders. It is noted that the appropriateness of conceptual design model has a big importance on the construction of lattice girder in the manufacturing fabrics of steel structures due to its practically applicability into the real world [19]. Hence, the waste of time in the elimination of inappropriate optimal designs obtained is prevented.

The generational optimal design procedure is utilized in the design optimization of steel structures with single objective function, for example, weight minimization. But the designer preferences are correspondingly neglected [20-21]. In order to handle this bottleneck, a multi-objective optimization procedure should be utilized in the optimal design of steel structures. Hence, it is possible to make a tradeoff analysis among the designer's preferences. Furthermore, the proposed multi-objective optimization approach has to also be capable of handling with the usage of mixing type of design variables due to the discrete nature of steel structures. Furthermore, it must own a simple but an effective search mechanism in order to reduce the computing time in the exploration of optimal designs with higher quality as well [17].

The effectiveness of any multi-objective optimization procedure depends on the properly assignment of their governing parameters. Thus, the computing performance of multi-objective optimization algorithm is correspondingly increased. But, the computing performance of proposed multi-objective optimization algorithm is degraded when the current parameter value set is utilized for the different optimization problem [22-24]. Thus, it is concluded that the adaptive usage of governing parameters is the most crucial issue in the evaluation of computing performance of multi-objective optimization algorithm since the form of solution space varies depending on the nature of optimization problem. The evaluation of multi-objective optimization procedures is distinguished from the ones with single objective due to the increased number of objective functions. The computing capability of any optimization procedure with single objective function is easily determined considering the convergence degree of optimal designs. However, the computing performance of multi-objective optimization procedure is assessed using a statistical test approach performed to evaluate the values of various quality criterions [25].

Particularly, the multi-objective optimization approaches that mimic the various nature-related phenomena such as, Darwin's evolutionary theory, livings of ants, bees, flying etc. are more successful in the design optimization of both steel structural and the other engineering applications [26]. Particularly, the genetic algorithm based multi-objective optimization algorithms achieve to

take more attention in the various optimization-related fields due to their simple and effective search mechanisms [27].

This study concerns with the optimal design of geometrically nonlinear tubular lattice girders considering the provisions of "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms: Load and Resistance: Factor Design (API RP2A-LRFD 1993) [28]. It is noted that API RP2A-LRFD is a compact design code since it comprises the member and joint-strength-related design codes. The arc-length method is employed to analyze the structural system in order to compute nonlinear structural responses at each load steps. The arc-length approach is proven to be successful in the identification of limit points, which indicates the failure in the stability of structural system, thereby iteratively tracing an equilibrium path formed by incremental load and displacement values [18]. Hence, the higher complex nonlinear structural problems that exhibits snap-through or snap-back behavior are easily solved through its capability of easily predicting the limit points (bifurcation, branching and etc.). An improved multi-objective optimization approach (ImpNSGAI) is utilized to execute the optimization-related computations [17]. The fundamentals of ImpNSGAI are constituted on the computing procedure of non-dominated sorting genetic algorithm II (NSGAI), which is basically governed by the genetic operators. The main future of ImpNSGAI is its ability of self adaptively adjusting the parameter values of genetic operators.

The novelty of this study comes from its being a first attempt to determine the load-resistance capability of the lattice girder at any load step of the nonlinear structural analysis approach thereby checking both member and joint strengths considering the provisions of API RP2A-LRFD specification [28]. The other novel aspect of this study is that the proposed optimal design approach does not penalized the objective functions. Hence, a waste of time consumed in the exploration of feasible designs is correspondingly prevented through this feature of the proposed design approach.

The presentation of optimal design results starts firstly by introducing a multi-objective optimization background. The computing steps of ImpNSGAI are defined in the subsequent sections. The design results outcome from the application examples, which were introduced in Reference [17], are also included. Then, a general summarization is reported in the section of "conclusion".

2. The basic elements of proposed optimization procedure

The design optimization of lattice girders that satisfies the economy, load-resistance and serviceability-related design conditions at the same time is carried out thereby minimizing the entire weight of lattice girder f_1 and joint displacements f_2 and maximizing its member forces f_3 (see Eqns. (1-3)). The proposed objective functions are formulated as:

$$f_1 = \min \left(\sum_{k=1}^m (w_k \cdot l_k) \right) \quad (k=1, \dots, m) \quad (1)$$

$$f_2 = \min(d_{ij}) \quad (i=1, \dots, 6 \text{ and } j=1, \dots, n) \quad (2)$$

$$f_3 = \max(f_{ij}) \quad (3)$$

The entire weight W is computed considering the structural member length l and its unit weight w for each member $(1, \dots, m)$. The properties of structural members with circular hollow shaped cross-sections are assigned from 37 different types-steel profiles. The joint displacements d_{ij} ($j=1, \dots, n$ and $i=1, \dots, 6$) are defined for both each degree of freedom i and joint j . The member forces f_{ij} , which contain "axial" & "shear" forces, "bending" & "torsional" moments, are obtained in the end of execution of nonlinear structural analysis.

The design constraints called as the member and joint related design constraints (MRDC and JRDC), are described using the member and joint strength-related inequalities. A unity value is assigned to represent these inequalities (see the sections of "D" and "E" in Reference [28]). For example, the inequalities ($f_i \leq \phi \cdot F$) for axial tension are represented by unities as $Unity_i = (f_i / \phi \cdot F) \leq 1.0$.

In the following part, the details of design constraints are presented including their formulation numbers along with Tables and Figures no's located in provisions of API RP2A-LRFD specification [28].

i) Member strength-related unities for m members ($k=1, \dots, m$):

$Unity_{Axial}^k$ represents the member axial capacity, which defines a strength against tensile and compressive stresses occurred in lattice girder members (see the section of D.2.1-1 and D.2.2-1 in Reference [28]). It is defined by making use of "nominal yield strength" and "nominal axial compressive strength", respectively. Whereas the nominal yield strength has a pre-assigned value, the nominal axial compressive strength is determined depending on both "nominal yield strength" and "elastic&inelastic local buckling strength" (stability issue). Therefore, the certain parameters, for example the effective length factor for the

calculation of braced length along with the gyration diameter and the ratio as "diameter/thickness", manage the magnitude of nominal axial compressive strength. Thus, the availability of diagonal members against the stability problem and the assignment of members with higher thickness for the construction of lattice girder has a big contribution to the member axial capacity.

$Unity_{Shear}^k$ represents the member's shear capacity, which defines a strength against shear stress occurred in lattice girder member (see the section of D.2.4-1 in Reference [28]). The shear capacity of member is determined considering "nominal shear strength", which is indicated as a percentage of "nominal yield strength". As in the $Unity_{Axial}^k$, the use of diagonal members provides to decrease the member forces, which comes from the external forces imposed on the corresponding nodes.

$Unity_{AxialCompr\&BendingBuckling}^k$ represents the member's combined axial compressive and bending buckling capacities, which defines the strengths against both compressive and bending stresses (see the section of D.3.2-2 [28]). This unity is computed depending on "euler buckling strength" and "nominal axial compressive strength" (stability issue) along with "nominal bending strength". The computing details about "nominal bending strength" are given in the introduction of $Unity_{Axial}^k$ above. The nominal bending strength is calculated depending on a ratio "diameter/thickness" and "elastic&plastic section modulus". Thus, the availability of diagonal members not only provides a positive contribution to this unity, but the use of members with higher thickness and plastic section modulus also increases the capacity of this unity.

$Unity_{AxialCompr\&BendingYield}^k$ represents the member's combined axial tensile and bending yield capacities, which defines the strengths against both tensile and bending forces (see the section of D.3.1-1 in Reference [28]). This unity is computed depending on "nominal inelastic buckling strength" and "nominal bending strength". The computing details about these strengths are given in the introduction of $Unity_{AxialCompr\&BendingBuckling}^k$ and $Unity_{Axial}^k$, respectively. Thus, the availability of diagonal members and the use of members with higher thickness and plastic section modulus provides an increase in the capacity of this unity.

ii) Joint strength-related unities for n joint ($j=1, \dots, n$):

$Unity_{JointAxial}^j$ represents the ultimate joint axial capacity, which indicates a strength against compressive&tensile and moment forces (see the section of E.3-2 in Reference [28]). Thus, the joint axial capacity is not only determined depending on axial forces, but also, in-plane and out-plane bending forces occurred in lattice girder members along with the joint types (K, T, Y and etc.). Considering, Table E.3-1 and Table E.3-2 in Reference [28], it is seen that K-shaped connections makes more contribution in the capacity of joint axial and thus leads to a decrease in the value of its unity (see Fig. E.3.2 in Reference [28]). Moreover, the contribution of T and Y-shaped connections are lower with respect to K-shaped connections. If a vertical member, axial force of which equals to zero, is connected with only one diagonal member at a joint, this joint is defined as T and/or T&Y. Therefore, the inclusion of diagonal members into the construction of lattice girder leads to an increase in the joint axial capacity. Particularly, the joint axial capacity, which is obtained by multiplying the "chord design factor" and "ultimate strength factor" is factorized by a parameter "connection resistance factor". In fact, both connection resistance factor and ultimate strength factor are determined the joint types (K, T, Y and etc.) along with the thickness and diameters of chord and brace members.

$Unity_{JointAxial\&Bending}^j$ represents the joint axial and bending capacities (see E.3-4 in Reference [28]). In fact, this unity is computing depending on the ultimate joint axial and bending moment capacities without omitting the parameter "connection resistance factor".

$Unity_{JointYield}^j$ represents the joint yield capacity (see the section of E.3-1 in Reference [28]). The strength of joint yield is determined depending on both the pre-defined yield values of brace and chord members and joint geometric properties (brace angle, thickness and diameters of brace and chord members).

It is mentioned that the thickness and diameters of chord and brace members have a big effect on the unity values which are utilized to define JRDCs. In his regard, some arrangements for these cross-sectional properties of chord and brace members provides an increase in the capacities of joint-related strengths as:

- i) The thickness of chord member must be higher with respect to its diameter.
- ii) The thickness of chord member must be higher than brace members'
- iii) The diameter of chord member must be higher than brace members'
- iv) Particularly, the lower angle θ between chord and brace members leads to an increase in the capacity of $Unity_{JointYield}^j$ (see Eqn. E.3-1 in Reference [28]). In this study, the lower value of middle height, which is indicated by Par_{H2} is utilized to indicate a lower angle θ . In fact, it has to be also noted that an increase in the middle height of lattice girder causes the occurrence of stability-related structural problem.

If any unities defined for the member and joint strength exceed "1", then nonlinear structural analysis is stopped at the corresponding loading step number. At the corresponding loading step number, maximum member force and

joint displacement values are utilized to determine both the load-resistance capability and joint displacements for the automatically assigned lattice girder configuration. It is mentioned that the arc-length method is utilized for the analysis of structural responses. For this purpose, a finite element analysis tool, ANSYS is employed to compute the responses for the current lattice girder configuration [17].

Furthermore, the design flexibility of proposed optimal design approach is improved thereby including an automatic lattice girder generating tool into the optimization of lattice girder designs taking into consideration of proposed constraints mentioned above. A typical lattice girder model is used to generate various lattice girders. Thus, it is possible to carry out not only sizing but also topologic and shape optimization at the same time. The size type design variables

$D1-D4$ and their cross-sectional properties are chosen from 37 different circular-hollow-shaped cross-sections and assuming their limit values Par_{UDV} and Par_{LDV} in a range of 1-37 (see Reference [17]). The topology type design variables, limits of which are defined by Par_{DNU} and Par_{DNL} , is governed by a ratio as (length of span LS / division number Par_{DN}). Two shape type design variables for two heights of lattice girder H1 and H2 are defined by two parameters Par_{H1} , Par_{H2} . Their limits are determined by the parameters Par_{H1U} , Par_{H1L} , Par_{H2U} and Par_{H2L} , respectively. A further detail about both the generation of various lattice girders and the assignment of the design-related parameters in connection with both the proposed generating tool and ANSYS is found in Reference [17].

```

WhichMethod=1 % WhichMethod=1 for NSGAII , WhichMethod=2 for ImpNSGAII
FitnessFunction = @ObjLatticeGirder;
%three type lattice girders are considered
Case=1
    if case==1
        ParDNU=15, ParDNL=5, ParLoS=393.700, ParH1U=35.433, ParH1L=23.622, ParH2U=23.622 and ParH2L=3.937, ParUDV=1 and ParLDV=37
    elseif case==2
        ParDNU=20, ParDNL=5, ParLoS=393.700, ParH1U=47.244, ParH1L=23.622, ParH2U=23.622 and ParH2L=3.937, ParUDV=1 and ParLDV=37
    elseif case==3
        ParDNU=40, ParDNL=10, ParLoS=787.401, ParH1U=59.055, ParH1L=31.496, ParH2U=31.496 and ParH2L=7.874, ParUDV=1 and ParLDV=37
    end
ub = [ParDNU ParLoS ParH1U ParH2U ParUDV ParUDV ParUDV ParUDV ]; % Lower bound
lb = [ParDNL ParLoS ParH1L ParH2L ParLDV ParLDV ParLDV ParLDV ]; % Upper bound
ParNNIN=10; ParGen=25, ParPopS=50, ParMutR=0.5, ParCrosR=0.5, ParCrosFrac=0.5, ParMigIn=2, ParMigFrac=0.5, ParSel=2,
    for i=1: ParNNIN
        options = gaoptimset('Generations', ParGen);
        options.PopulationSize= ParPopS;
        options.MutationFcn= { @mutationuniform, ParMutR };
        options.CrossoverFcn= { @crossoverheuristic, ParCrosR };
        options.CrossoverFraction= ParCrosFrac;
        options.MigrationInterval= ParMigIn;
        options.MigrationFraction= ParMigFrac;
        options.SelectionFcn={ @selectiontournament, ParSelR };

        gamultiobj
            % Validate constraints and options
        gacommon
            % Call appropriate multi objective optimization solver
        gamultiobjsolve
            gamultiobjMakeState % Create initial state: population, Evaluate fitness functions
            feval(options.CreationFcn) % Evaluate fitness function to get the number of objectives
            Fcnvectorizer % Evaluate fitness function to get the number of objectives
            rankAndDistance % Get the rank and distance measure of the population
            gadsplot; gaoutput % Give the plot/output Functions
            while true % check to see if any stopping criteria have been met
                gamultiobjConverged
                stepgamultiobj
                migrate % Migration
                gadsplot; gaoutput % Give the plot/output Functions
                if WhichMethod==2
                    ALLoutput=[output.averagedistance, output.spread]
                    ALLinput=[ALLinput ParGen; ParPopS; ParMutR; ParCrosR; ParCrosFrac; ParMigIn; ParMigFrac; ParSelR];
                    ALLinput=NeuralNetworkImp(ALLinput, ALLoutput)
                end
            end
    end
end

```

Fig. 1 A Matlab Script for ImpNSGAII and NSGAII

3. An improved multi-objective optimization algorithm named Imp-NSGAII

It is mentioned that the nature-inspired multi-objective algorithms are mostly preferred in the design optimization of structural engineering applications due to their both higher search capabilities and simple search mechanisms. Particularly, the genetic algorithms (GAs), a branch of evolutionary algorithms has been accomplished to take more attention in the various engineering areas, particularly structural engineering applications [29-36]. Therefore, their fundamentals have been frequently utilized to arrange the basic elements of multi-objective optimization approaches.

The genetic algorithm approach completely mimics the main fundamentals of Darwin's evolutionary theory. Firstly, the decision (design) variables of optimization problem are appropriately coded in a *chromosome*. Then, the objective functions, which evaluate *fitness* (an indicator for the quality of chromosome), are determined depending on the preferences of designer. A number of *individuals* composed from *chromosomes* are gathered to form a *population*. Then, the individuals with a higher fitness values are *selected*, *mutated* and *reproduced* to form the next population. This *generation process* called *evolution* is stopped when a termination condition, for example a predefined generation number is fulfilled. This simple but effective search strategy of genetic algorithm has played a big role in the emergence of trend multi-objective optimization algorithms. The most popular one of these algorithms is NSGAII due to

having a wide range usage in the various scientific fields [27]. The working principle of NSGAI is fundamentally based on the usage of genetic operators of GAs (crossover, mutation and selection) in the generation of promising individuals for next populations. Firstly, it is assumed that the individuals are collected in the different sparse and crowded regions of solution space. Then, the individuals are ranked considering the locations of these regions. In other words, *crowding distance values* of individuals are ranked taking into account of *pareto ranking mechanism*, which is responsible to assign a rank value began from 1 to the individuals. Thus, the best ranking individuals are selected and re-produced in order to generate the next populations. Therefore, the governing parameter values of genetic operators have a big impact on the computing capability of NSGAI. Although it is possible to determine the appropriate values of genetic operator parameters thereby trying their different combination sets, this approach will become not to be practical taking into account of its usage for a different design problem. In order to overcome this bottleneck, NSGAI is improved in a way of being utilized the neural network [17]. ImpNSGAI is basically based on adapting the parameter values of genetic operators throughout the evolutionary search thereby measuring the approximating and diversity degree of individuals in current population. The computing steps of ImpNSGAI are accordingly coded in MATLAB [37].

According to the pseudo code in Fig. 1, the fitness functions $f1$, $f2$ and $f3$ coded in a separate toolbox “FitnessFunction” are computed considering the population x^0 , which is arranged according to the limits of design variables lb & ub (see Eqns. (4-6)). Although the maximum design variable number “numberOfVariables” is taken as 8 (see Eqns. (4-6)), it is noted that the size of row matrix named $ParDN$ is determined depending on the number of size type design variables. The current optimization procedure named NSGAI and coded in MATLAB [37] is essentially governed by a structure field, option. This structural field contains both the genetic operators and their corresponding parameter values. Firstly, the toolbox “Gamultiobj”, which contains the upper and lower limits of constraints along with the corresponding parameter names and values, is activated. Thus, the fitness functions are correspondingly computed considering the pre-defined design constraints. The toolbox “gamultiobjsolve”, which automatically runs the two toolboxes “GamultiobjMakeState” and “stepgamultiobj” has a responsibility of computing the procedure of NSGAI. In fact, “GamultiobjMakeState”, which is responsible to perform both the genetic operations such as selection, crossover, mutation and the quality measuring-related

computation, is utilized in run of “stepgamultiobj”. (see ROUTINE2 for a further detail about “GamultiobjMakeState” in Reference [17]). The toolbox “gamultiobjsolve” firstly runs the other toolbox “GamultiobjMakeState” for forming the beginning population in a way of utilizing options. CreationFcn, calculate the fitness functions by “fcnvectorizer” and correspondingly order the fitness functions by “rankAndDistance”. Following activation of “stepgamultiobj”, the main generation is terminated depending on the value of parameter “options”. Generations. It is noted that it is defined a number of termination options in the command “gamultiobjConverged”. “Stepgamultiobj” is employed to execute the genetic operations (see ROUTINE1 in Reference [17]). It is noted that two toolboxes “gadsplo” and “gaoutput” can be utilized to plot a number of different outputs, following the execution of migration-related operations.

$$x^0 = \left[\underbrace{fix(x_1^0)}_{Par_{DN}}, LS, \underbrace{x_2^0, x_3^0}_{Par_{H1} \text{ and } Par_{H2}}, \underbrace{fix(x_4^0), fix(x_5^0), fix(x_6^0), fix(x_7^0)}_{Par_{DV}} \right] \quad (4)$$

$$ub = \left[\underbrace{Par_{DNU}}_{Par_{DN}}, LS, \underbrace{Par_{H1U}, Par_{H2U}}_{Par_{H1} \text{ and } Par_{H2}}, \underbrace{Par_{UDV}, Par_{UDV}, Par_{UDV}, Par_{UDV}}_{Par_{DV}} \right] \quad (5)$$

$$lb = \left[\underbrace{Par_{DNL}}_{Par_{DN}}, LS, \underbrace{Par_{H1L}, Par_{H2L}}_{Par_{H1} \text{ and } Par_{H2}}, \underbrace{Par_{LDV}, Par_{LDV}, Par_{LDV}, Par_{LDV}}_{Par_{DV}} \right] \quad (6)$$

The governing parameters of both ImpNSGAI and NSGAI are defined in the structure field “options” as “options.Generations” Par_1 , “options. PopulationSize” Par_2 , “options. MutationFcn { @mutationuniform. }” Par_3 , “options. CrossoverFcn { @crossoverheuristic. }” Par_4 , “options. CrossoverFraction” Par_5 , “options. MigrationInterval” Par_6 , “options. MigrationFraction” Par_7 , “options. SelectionFcn { @selectiontournament. }” Par_8 ,

Table 1
The Governing Parameter Values of ImpNSGAI and NSGAI

Governing Parameters	ParNNN (ImpNSGAI)									
	1	2	3	4	5	6	7	8	9	10
Par_1	22	3	20	19	21	16	15	11	17	4
Par_2	36	42	34	34	30	29	30	26	15	16
Par_3	0.7099	0.4629	0.7059	0.6367	0.5906	0.4630	0.4550	0.4258	0.9034	0.4446
Par_4	0.4990	0.3951	0.7810	0.4712	0.2297	0.8838	0.9060	0.1529	0.2113	0.3037
Par_5	0.7356	0.7848	0.5574	0.7881	0.7740	0.2621	0.3183	0.6292	0.2972	0.4280
Par_6	2	4	3	3	4	3	4	2	2	5
Par_7	0.3316	0.8239	0.9441	0.9397	0.9543	0.5917	0.2362	0.6962	0.5181	0.8556
Par_8	0.5863	0.4983	0.9625	0.1392	0.4255	0.8895	0.6899	0.4745	0.4170	0.6502
Governing Parameters	ParNNN=1 (NSGAI)									
	1									
Par_1	100									
Par_2	50									
Par_3	0.5									
Par_4	0.5									
Par_5	0.5									
Par_6	5									
Par_7	0.5									
Par_8	0.5									

See the definitions of abbreviations for the governing parameters in Section 3

4. Discussion of results

In this study, the member and joint-related strength design constraints are taken from API RP2A-LRFD specification [28]. The influences of MRDC and JRDC on the optimality qualities of designs are investigated. Furthermore, the computing capability of ImpNSGAI is also compared by NSGAI algorithm including the other optimization approaches proposed in Literature. A bench-

mark lattice girder and a general lattice girder, configuration of which are automatically generated depending on a user-defined loading adjustment and spanning length are devised as the application design examples. In fact, these design problems were also optimized considering only MRDC in Reference [17]. Thus, it was shown that the optimal configurations of lattice girders simultaneously satisfied the economy, load-resistance and serviceability-related design conditions. It is noted that the load-resistance capability of lattice girders is determined according to the member forces.

Table 2

Extreme Optimal Designs (OD) and Corresponding Design (D) Values (Design Example 1)

	Size Type Design Variables ^{a1}																
	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17
OD1 (MW)	PIPEST 6 ^{a2} (5.22 in ³)	PIPEST 3 1/2 ^{a3} (3.44 in ³)	PIPEST 4 (4.14 in ³)	PIPEST 3 1/2 (3.44 in ³)	PIPEST 2 1/2 ^{a4} (3.81 in ³)	PIPEST 3 (5.16 in ³)	PIPEST 4 (4.14 in ³)	PIPEST 3 1/2 (3.44 in ³)	PIPEST 2 1/2 (3.81 in ³)	PIPEST 3 1/2 (3.44 in ³)	PIPEST 4 (4.14 in ³)	PIPEST 3 1/2 (3.44 in ³)	PIPEST 3 (5.16 in ³)	PIPEST 4 (4.14 in ³)	PIPEST 3 (5.16 in ³)	PIPEST 3 1/2 (3.44 in ³)	PIPEST 3 (5.16 in ³)
OD2 (MJD)	PIPEST 12 (17.9 in ³)	PIPEST 6 (14.70 in ³)	PIPEST 8 (20.00 in ³)	PIPEST 6 (14.70 in ³)	PIPEST 10 (15.00 in ³)	PIPEST 12 (13.60 in ³)	PIPEST 8 (20.00 in ³)	PIPEST 6 (14.70 in ³)	PIPEST 10 (15.00 in ³)	PIPEST 6 (14.70 in ³)	PIPEST 8 (20.00 in ³)	PIPEST 6 (14.70 in ³)	PIPEST 12 (17.9 in ³)	PIPEST 8 (20.00 in ³)	PIPEST 12 (17.9 in ³)	PIPEST 6 (14.70 in ³)	PIPEST 12 (17.9 in ³)
OD3 (MEF)	PIPEST 8 (20.00 in ³)	PIPEST 6 (14.70 in ³)	PIPEST 12 (13.60 in ³)	PIPEST 6 (14.70 in ³)	PIPEST 12 (17.90 in ³)	PIPEST 10 (15.00 in ³)	PIPEST 12 (13.60 in ³)	PIPEST 6 (14.70 in ³)	PIPEST 12 (17.90 in ³)	PIPEST 6 (14.70 in ³)	PIPEST 12 (13.60 in ³)	PIPEST 6 (14.70 in ³)	PIPEST 10 (15.00 in ³)	PIPEST 12 (13.60 in ³)	PIPEST 10 (15.00 in ³)	PIPEST 6 (14.70 in ³)	PIPEST 10 (15.00 in ³)
Ref. [38] (in ³)	15.821	0.108	11.996	0.100	8.150	5.507	11.829	0.100	7.934	0.100	4.093	0.100	5.660	4.061	5.656	0.100	5.582
Ref. [39] (in ³)	15.930	0.100	12.070	0.100	8.067	5.562	11.993	0.100	7.945	0.100	4.055	0.100	5.657	4.000	5.558	0.100	5.579
Ref. [40] (in ³)	15.896	0.103	12.092	0.100	8.063	5.591	11.915	0.100	7.965	0.100	4.076	0.100	5.670	3.998	5.548	0.103	5.537
	Entire Weight					Joint Displacement					Maximum Member Force and Stress					Load Step Number	
Des1 (MW)	2515.895 lb ^{a1} 1539.907 lb ^{a5}					1.217 in ^{a1} 1.492 in ^{a5}					240.033 ^{a1} and 25.87 ksi ^{a1} 239.958 and 29.83 ksi ^{a5}					2 ^{a1} 2 ^{a5}	
Des2 (MJD)	9416.272 lb 6386.020 lb					0.288 in 1.999 in					240.000 and 6.200 ksi 1239.191 and 47.89 ksi					2 3	
Des3 (MEF)	9134.793 lb 9847.947 lb					1.605 in 1.513 in					1240.584 and 40.87 ksi 1240.472 and 36.80 ksi					3 3	
Ref. [38]	2580.81 lb					N/A					N/A					N/A	
Ref. [39]	2581.89 lb					N/A					N/A					N/A	
Ref. [40]	2581.94 lb					N/A					N/A					N/A	

a1: According to Displacement, Member and Joint-related Design Constraints

a2: PIPST (Standard Tubular Cross-sections)

a3: PIPEST (Extra Strong Tubular Cross-sections)

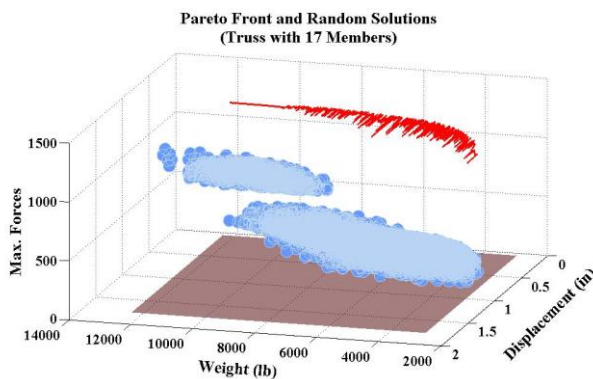
a4: PIPEEST (Double-Extra Strong Tubular Cross-sections)

a5: According to Displacement, Member-related Design Constraints [17])

MW: Minimum Weight Value

MJD: Minimum Joint Displacement Value

MMF: Maximum Member Force Value

**Fig. 2** True Pareto front Design Example 1

4.1. A benchmark lattice girder design

This structural system is subject to a joint load of 100 klpf on the joint number 9. It is defined as Design Example 1. The optimal design this simple lattice girder was firstly carried out in References [38-40].

True pareto front with a red color obtained using JRDC&MRDC is presented Fig. 2. The governing parameters of relatively successful ImpNSGAI and NSGAI are presented in Table 1.

In order to make a further investigation into the influence of JRDC on the optimality quality of designs obtained, some extreme designs are tabulated in Table 2. Considering Table 2, the minimum values of entire weight obtained using JRDC are higher than ones obtained using MRDC. It is clear that an inclusion of JRDC into the design constraints causes to increase the construction cost of optimal design.

This claim is also confirmed considering Fig. (3-5). Considering Fig. (3-5), it is shown that the termination number of load steps is almost 3 for both MRDC and JRDC. But, the unity values of JRDC are higher than the MRDC (see Fig.

3g and 5g). Thus, it is said that the influence of JRDC on the quality of optimal design has a big impact compared to MRDC.

When the unity values in Fig. (3-5) are considered, it is observed two design constraints named axial compression&bending buckling and joint yield has a big effect on the optimality quality of extreme designs compared MRDC due to their higher values (see Fig. 3c,4c,5c,3g,4g and 5g). In case of using the JRDC and MRDC at the same time, it is also shown that the axial forces have a relatively higher importance on the optimality quality of extreme designs due to their higher values (see Fig. 3a,3c,4a,4c,5a and 5c).

Moreover, the variation of their unity values with respect to the member (element) and joint (node) number is also sketched using bar-charts in Fig. 6. Considering Fig. 6, it is seen that the load step numbers indicated the termination of nonlinear structural responses are identical for both MRDC and JRDC.

The important reason behind the similarity between results obtained is the fixed geometry and framing configuration of benchmark design example with 17 members. It is expected that a change in the framing configuration of benchmark lattice girder leads to an activation of different JRDC and MRDC. This expected result will be examined in the next design example with varying geometry and framing configurations.

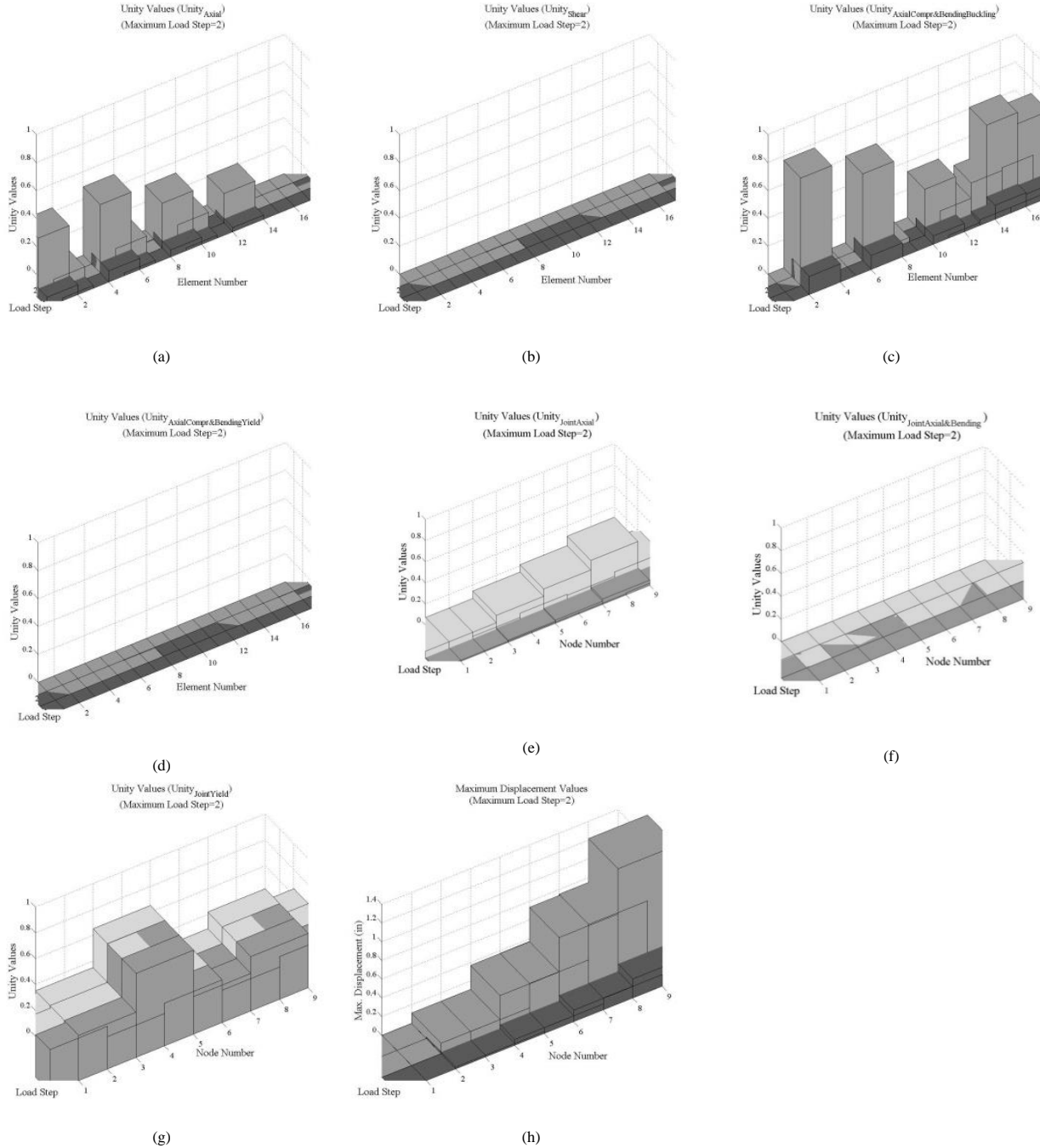


Fig. 3 Variation in The Unity Values of MRDC (a-d), JRDC (e-g), Joint Displacements (h) According to Load Steps Obtained for Minimum Weight (see Design Example 1 in Table 2)

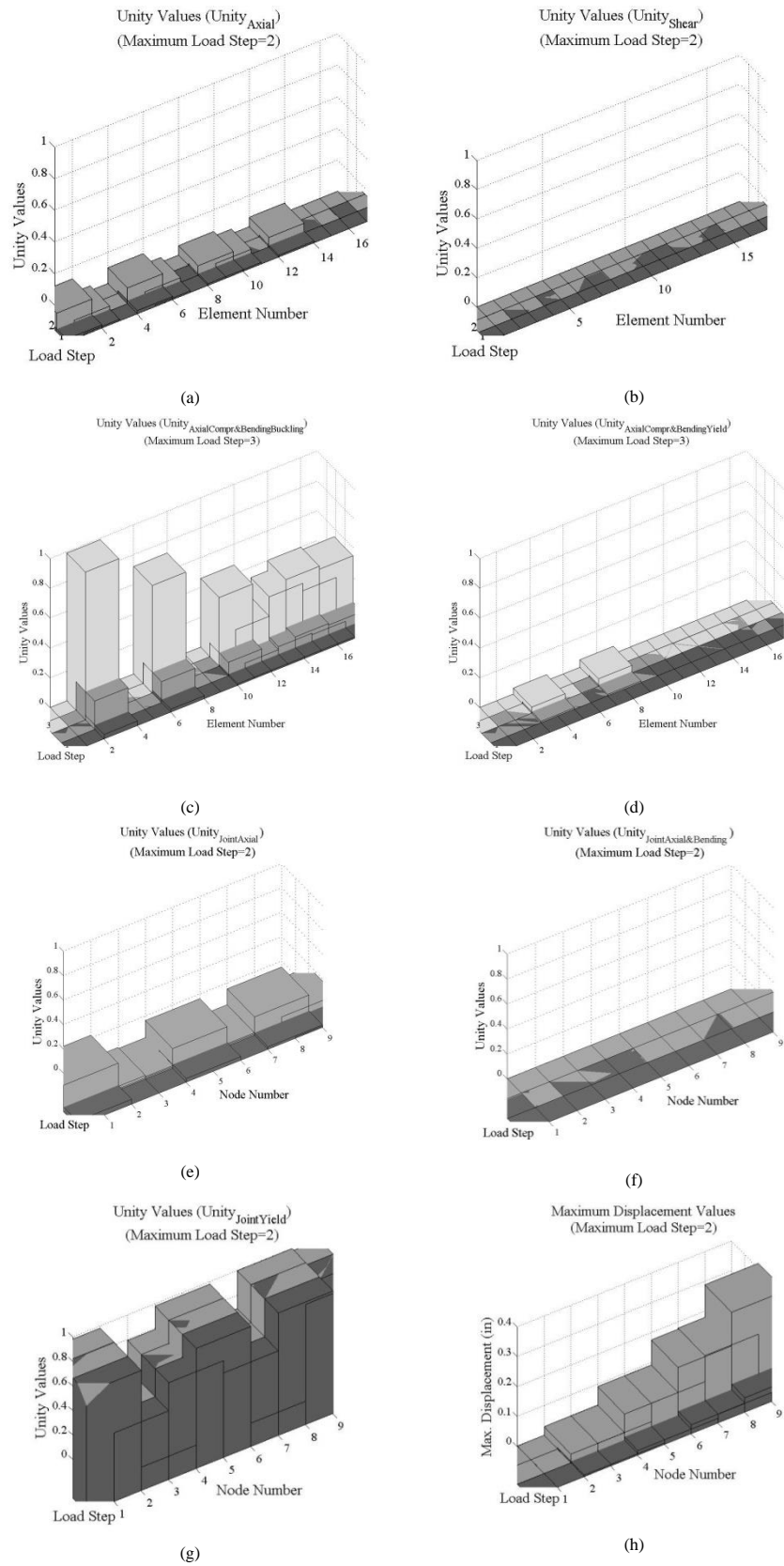


Fig. 4 Variation in The Unity Values of MRDC (a-d), JRDC (e-g), Join Displacements (h) According to Load Steps Obtained for Minimum Displacement (see Design Example 1 in Table 2)

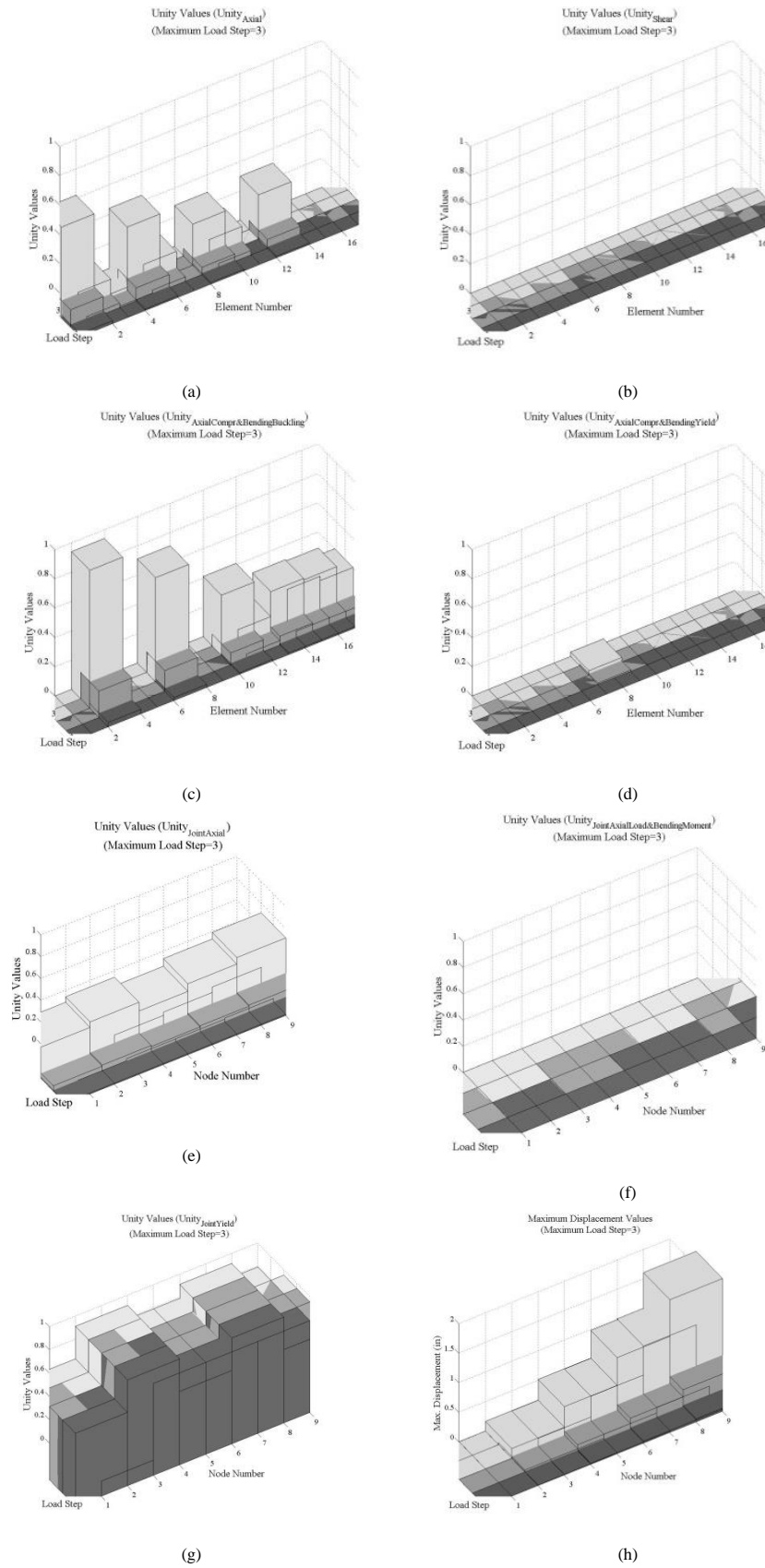


Fig. 5 Variation in The Unity Values of MRDC (a-d), JRDC (e-g), Joint Displacements (h) According to Load Steps Obtained for Maximum Critical Load (see Design Example 1 in Table

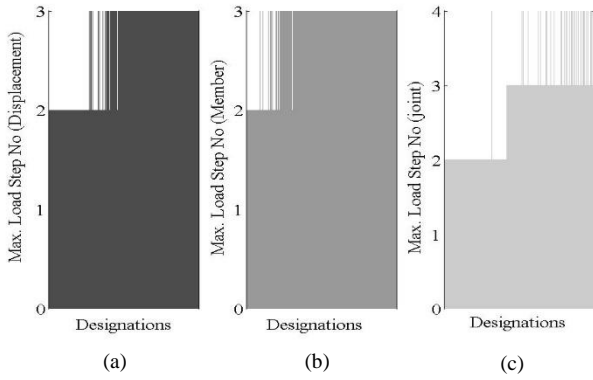


Fig. 6 The Maximum Load Step Numbers (see Table 2)

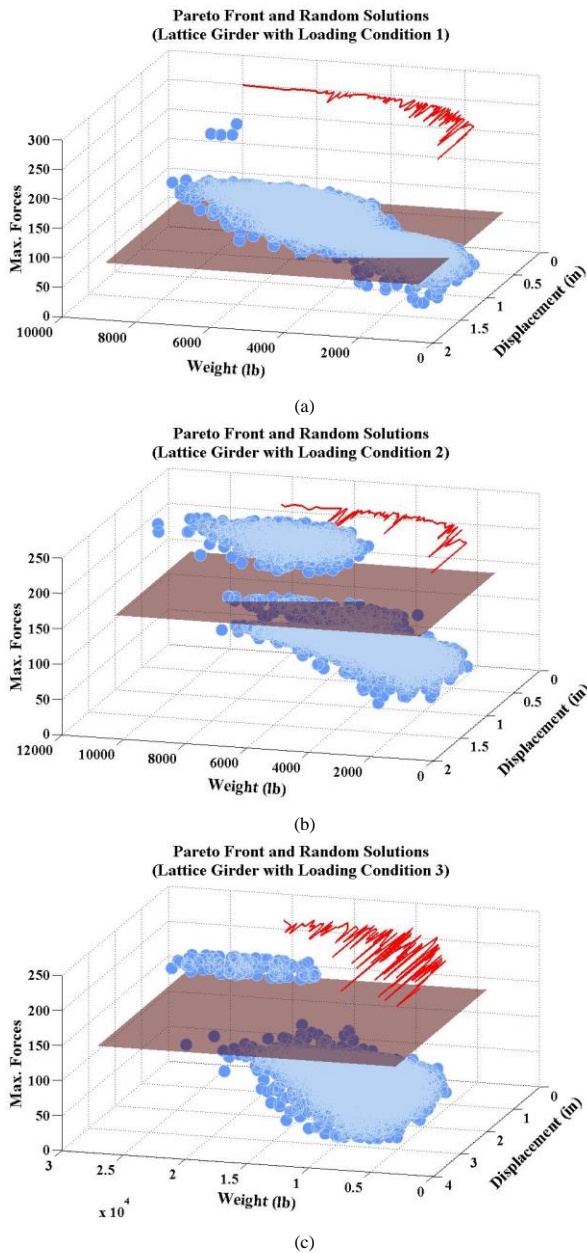


Fig.7 True Pareto Fronts for Lattice Girder1 (a) and Lattice Girder2 (b) and Lattice Girder3 (c)

4.2. A general lattice girder

In this design example, a lattice girder with three spanning lengths and loading adjustments are automatically generated at the design stage and defined as Design Example 2 (see Table 3). Hence, it will be possible to determine the

relative effectiveness of JRDC and MRDC on the quality of optimal design. For this purpose, the upper joints of lattice girder, numbers of which is obtained assuming as (length of span LS /division number Par_{DN}). The design complexity of lattice girder is sequentially increased in a way of applying three different combination cases of total load and spanning length to the lattice girder automatically generated (see Table 3). Hence, the influence of JRDC on the optimality quality of lattice girder designs is also investigated depending on the severe loading conditions and spanning lengths.

True pareto fronts obtained using JRDC&MRDC are presented Fig. 7 for three different loading&spanning cases. The governing parameters of relatively successful ImpNSGAI and NSGAI is presented in Table 4.

The results obtained from the design optimization of lattice girder, which has an increasing design complexity (see Tables (5-6)) are firstly categorized considering the proposed design unities along with the three different loading&spanning cases and figured in Fig. (8-14) instead of presenting all of the unity values as in section of benchmark lattice girder design. Then, these results are summarized in the following two different grouping (see Table 7). Moreover, the variation in the load steps with respect to the multiple objective functions considering the optimal designs obtained from the execution of proposed optimization tool is also included (see Fig. 15).

The influence of JRDC on the optimality quality of optimal designs is investigated in conjunction with MRDC. The variation in MRDC and JRDC unities are presented in Fig. (8-14) The extreme optimal designs are reported for three cases of lattice girder in Tables (5-6) and also summarized in Table 7 considering the critical values of related unities. It is noted that the optimal designs in Table 6 corresponds to the feasible design solutions corresponding to the higher load value. The tabulated data in Tables (5-6) contains the resulted size type design variables $D1-D4$, shape type design variables Par_{H1} , Par_{H2} , topology type design variables Par_{DN} of lattice girders including their objective function values and corresponding framing representations. Furthermore, the each of these extreme optimal designs is sketched using bar charts to illustrate the varying values of JRDC and MRDC-related unities with respect to the load steps outcome from the nonlinear structural analysis (see Fig. 15).

It is mentioned that the cross-sectional properties for the members of lattice girders assigned in a way of using the steel profiles which contains 37 different circular-hollow-shaped cross-sections. These circular-hollow-shaped cross-sections are categorized in three different type class: “standard”, “extra strong” and “double extra strong”. In fact, this categorization is made depending on an increase in the cross-sectional thickness and related cross-sectional properties.

The values of $Unity_{Axial}$ and $Unity_{Shear}$ are increased due to a decreased use of diagonal members in the construction of tubular lattice girder, which have a responsibility to decrease both the shear and the axial forces of each members connected to a single node. In fact, the other negative effect is arisen from the use of steel profiles with standard type tubular cross-sections instead of double extra and extra strong ones (see Fig. (8-9) and Tables (5-6)). In general, the weight minimization is not only one of the main reasons behind the higher values of these unities, but the maximization of forces has also a relative responsibility (see Table 7).

The increased assignment of steel profiles with the standard type tubular cross-sections to the member of lattice girder causes to increase the values of $Unity_{AxialCompr\&BendingBuckling}$ and $Unity_{AxialCompr\&BendingYield}$ due to the decrease in the two profile cross-sectional properties, the diameter and the plastic section modulus (see Fig. (10-11) and Tables (5-6)). In general, the weight minimization has a responsibility of increasing the values of these unities (see Table 7).

The use of steel profiles with decreased diameter and thickness as a chord member rather than a brace member causes to an increase in the values of $Unity_{JointAxial}$ and $Unity_{JointAxial\&Bending}$ (see Fig. (12-13) and Tables (5-6)). The maximization of member forces has a main responsibility in the increase of these unities. But it is also noted that this increase is also relatively arisen from the weight minimization (see Table 7).

An increase in the middle height of lattice girder along with the use of decreased cross-sectional thickness for the chord members, which is indicated by Par_{H2} , causes to elevate the values of $Unity_{JointYield}$ (see Fig. 14 and Table 7-8). Whereas the minimization of joint displacement generally leads to an increase in the value of $Unity_{JointYield}$, the weight minimization also increases this unity value (see Table 7).

The contribution of JRDC to the optimal lattice girder design is also clarified by examining the maximum load step numbers (see Fig. 7). Considering Fig. 7, it is seen that the load steps numbers corresponding to both JRDC and MRDC are equally terminated. This result implies that the inclusion of JRDC into the current design constraints regarding to MRDC affects the quality of optimal designs. Furthermore, the obvious evidence that supports this claim has already presented with the lower values of maximum member forces obtained using JRDC with respect to the higher maximum member forces obtained using the MRDC (see Tables (5-6)).

Table 3
The Proposed Lattice Girder Patterns and Corresponding Values of Their Design Variables










	Lattice Girder 1	Lattice Girder 2	Lattice Girder 3
Arrangements for Spanning, Loading and Material Conditions			
Assignments to Describe The General Structural System			
Total Load Value	70 kipf	140 kipf	150 kipf
Length of Span	393.70 in.	393.70 in.	787.40 in.
Maximum Node Deflection.	3.94 in		
Material Yield Value	36 ksi		
Elasticity Module	29732 ksi		
Arrangements for Size Type Parameter Par_{ND}			
Par_{ND}	4	4	4
Par_{UDV}	37	37	37
Par_{LDV}	1	1	1
Arrangements for Topology Type Parameter Par_{ND}			
Par_{UDN}	15	20	40
Par_{LDN}	5	5	10
Arrangements for Shape Type Parameters Par_{H1} and Par_{H2}			
Par_{UH2}	35.433 in.	47.244 in.	59.055 in.
Par_{LH2}	23.622 in.	23.622 in.	31.496 in.
Par_{UH1}	23.622 in.	23.622 in.	31.496 in.
Par_{LH1}	3.937 in.	3.937 in.	7.874 in.

Table 4
The Governing Parameter Values of ImpNSGAI and NSGAI

Governing Parameters	Par_{NNIN} (ImpNSGAI)									
	1	2	3	4	5	6	7	8	9	10
Par_1	11	2	13	23	20	6	2	17	19	4
Par_2	26	30	45	35	23	37	45	49	25	38
Par_3	0.9395	0.5844	0.5096	0.9253	0.2656	0.8872	0.4593	0.2620	0.6779	0.7484
Par_4	0.5498	0.3828	0.2768	0.7763	0.2533	0.6058	0.1762	0.8198	0.5180	0.2030
Par_5	0.4906	0.2777	0.7328	0.1986	0.6586	0.3603	0.5689	0.2499	0.4431	0.4590
Par_6	2	2	3	3	3	4	3	3	5	2
Par_7	0.3672	0.5450	0.3270	0.9784	0.2720	0.4395	0.4759	0.1527	0.7711	0.6486
Par_8	0.6337	0.5551	0.4679	0.4774	0.4204	0.1606	0.4266	0.9318	0.3035	0.8082
Governing Parameters	$Par_{NNIN}=1$ (NSGAI)									
	1									
Par_1	100									
Par_2	50									
Par_3	0.5									
Par_4	0.5									
Par_5	0.5									
Par_6	5									
Par_7	0.5									
Par_8	0.5									


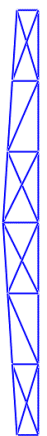
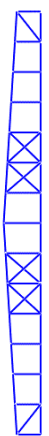


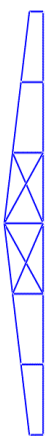



See the definitions of abbreviations for the governing parameters in Section 3

Table 5
Extreme Optimal Design (OD) Values (Design Example 2)

	Lattice Girder 1 ^{a1} (Length of Span=393.7 in. Total Load Value=70 kipf)			Lattice Girder 2 ^{a1} (Length of Span=393.7 in. Total Load Value=140 kipf)			Lattice Girder 3 ^{a1} (Length of Span=787.4 in. Total Load Value=150 kipf)		
	OD1 (MW)	OD2 (MJD)	OD3 (MMF)	OD4 (MW)	OD5 (MJD)	OD6 (MMF)	OD7 (MW)	OD8 (MJD)	OD9 (MMF)
Par _{DN}	14	10	14	6	8	6	22	22	20
Par _{H1}	13.973	23.272	22.065	5.925	22.372	15.705	29.998	28.857	17.219
Par _{H2}	24.818	34.858	34.089	33.076	42.666	44.371	44.018	58.837	54.524
D1	PIPEEST 2	PIPEEST 6	PIPEEST 6	PIPOST ^{a2} 5	PIPEST 12	PIPOST 10	PIPEEST 3	PIPOST 12	PIPEST 12
D2	PIPOST 2 1/2	PIPEST 10	PIPEST 12	PIPOST 4	PIPEEST 6	PIPEST 10	PIPEST 4	PIPEST 12	PIPEST 12
D3	PIPOST 2 1/2	PIPOST 12	PIPEEST 6	PIPEST 5	PIPOST 10	PIPEST 12	PIPOST 2 1/2	PIPEST 10	PIPEST 10
D4	PIPEST 2	PIPEEST 6	PIPEST 6	PIPOST 6	PIPOST 12	PIPEEST 5	PIPEST 2	PIPEEST 5	PIPOST 10
Entire Weight	878.748 lb ^{a1} 811.389 lb ^{a5}	7909.296 lb 3567.378 lb	6694.965 lb 6062.082 lb	1283.259 lb 1167.992 lb	7744.226 lb 2437.039 lb	5192.960 lb 3860.235 lb	3263.167 lb 3041.241 lb	15689.944 lb 11250.487 lb	15317.896 lb 12847.894 lb
Joint Displacement	1.319 in ^{a1} 1.242 in ^{a5}	0.0747 in 1.768 in	0.315 in 1.138 in	1.307 in 0.897 in	0.095 in 1.912 in	0.846 in 0.944 in	3.007 in 2.576 in	0.489 in 3.932 in	2.962 in 2.912 in
Member Force	20.958 ^{a1} 21.002 ^{a5}	20.998 108.392	45.335 255.086	41.980 41.951	41.991 41.923	216.962 217.007	44.924 44.979	44.988 44.925	232.168 232.224
Load Step Number	2 ^{a1} 2 ^{a5}	2 3	2 3	2 2	2 2	3 3	2 2	2 2	3 3
									

See the definitions for sub&superscripts and other abbreviations in Table 2

Table 6
Extreme Optimal Design (OD) Values (Design Example 2)

	Lattice Girder 1 ^{a1} (Length of Span=393.7 in. Total Load Value=70 kipf)			Lattice Girder 2 ^{a1} (Length of Span=393.7 in. Total Load Value=140 kipf)			Lattice Girder 3 ^{a1} (Length of Span=787.4 in. Total Load Value=150 kipf)		
	OD10 (MW)	OD11 (MJD)	OD12 (MMF)	OD13 (MW)	OD14 (MJD)	OD15 (MMF)	OD16 (MW)	OD17 (MJD)	OD18 (MMF)
Pa _{FDN}	6 ^{a1}	6	14	6	6	6	16	30	20
Pa _{TH1}	15.731 ^{a1}	19.692	22.065	10.819	17.521	15.705	20.036	27.091	17.219
Pa _{TH2}	34.739 ^{a1}	32.518	34.089	42.646	45.525	44.371	59.027	58.437	54.524
D1	PIPEST 10	PIPEST 12	PIPEEST 6	PIPEST 10	PIPEST 12	PIPEST 10	PIPEST 12	PIPEST 12	PIPEST 12
D2	PIPEST 6	PIPEST 12	PIPEST 12	PIPEST 10	PIPEST 12	PIPEST 10	PIPEST 12	PIPEST 12	PIPEST 12
D3	PIPEST 3	PIPEST 10	PIPEEST 6	PIPEST 10	PIPEEST 4	PIPEST 12	PIPEST 8	PIPEEST 5	PIPEST 10
D4	PIPEST 3 1/2	PIPEST 12	PIPEST 6	PIPEST 12	PIPEST 10	PIPEEST 5	PIPEEST 5	PIPEST 10	PIPEST 10
Entire Weight	2533.081 lb ^{a1} 2137.142 lb ^{a5}	7819.537 lb 3567.378 lb	6694.965 lb 6062.082 lb	4057.222 lb 3804.047 lb	6783.367 lb 6589.918 lb	5192.960 lb 3860.235 lb	12234.631 lb 11348.644 lb	19880.220 lb 20222.117 lb	15317.896 lb 12847.894 lb
Joint Displacement	0.975 in ^{a1} 1.072 in ^{a5}	0.307 in 1.768 in	0.315 in 1.138 in	1.048 in 0.934 in	0.458 in 1.507 in	0.846 in 0.944 in	2.786 in 2.798 in	0.429 in 3.569 in	2.962 in 2.912 in
Member Force	108.416 ^{a1} 108.348 ^{a5}	108.452 108.392	45.335 255.086	216.902 216.887	216.880 216.658	216.962 217.007	232.028 232.131	44.987 232.096	232.168 232.224
Load Step Number	3 ^{a1} 3 ^{a5}	3 3	2 3	3 3	3 3	3 3	3 3	2 3	3 3
									

See the definitions for sub& superscripts and other abbreviations in Table 2

Table 7

The Categorization of Extreme Optimal Designs Considering The Critical Unities (see Table 5-6)

	Lattice Girder 1 (Length of Span=393.7 in. Total Load Value=70 kipf)			Lattice Girder 2 (Length of Span=393.7 in. Total Load Value=140 kipf)			Lattice Girder 3 (Length of Span=787.4 in. Total Load Value=150 kipf)			Lattice Girder 1 (Length of Span=393.7 in. Total Load Value=70 kipf)			Lattice Girder 2 (Length of Span=393.7 in. Total Load Value=140 kipf)			Lattice Girder 3 (Length of Span=787.4 in. Total Load Value=150 kipf)		
	MW	MJD	MMF	MW	MJD	MMF	MW	MJD	MMF	MW	MJD	MMF	MW	MJD	MMF	MW	MJD	MMF
	OD1	OD2	OD3	OD4	OD5	OD6	OD7	OD8	OD9	OD10	OD11	OD12	OD13	OD14	OD15	OD16	OD17	OD18
<i>Unity_{Axial}</i>	●			●					●	●						●		
<i>Unity_{Shear}</i>			●	●					●	●			●					●
<i>Unity_{AxialCompr} & BendingBuckling</i>	●			●					●	●			●			●		
<i>Unity_{AxialCompr} & BendingYield</i>	●			●					●	●			●			●		
<i>Unity_{JointAxial}</i>	●								●	●					●	●		
<i>Unity_{JointAxial} & Bending</i>			●			●			●	●					●	●		
<i>Unity_{JointYield}</i>		●			●			●				●	●			●		

See the definitions for abbreviations in Table 2

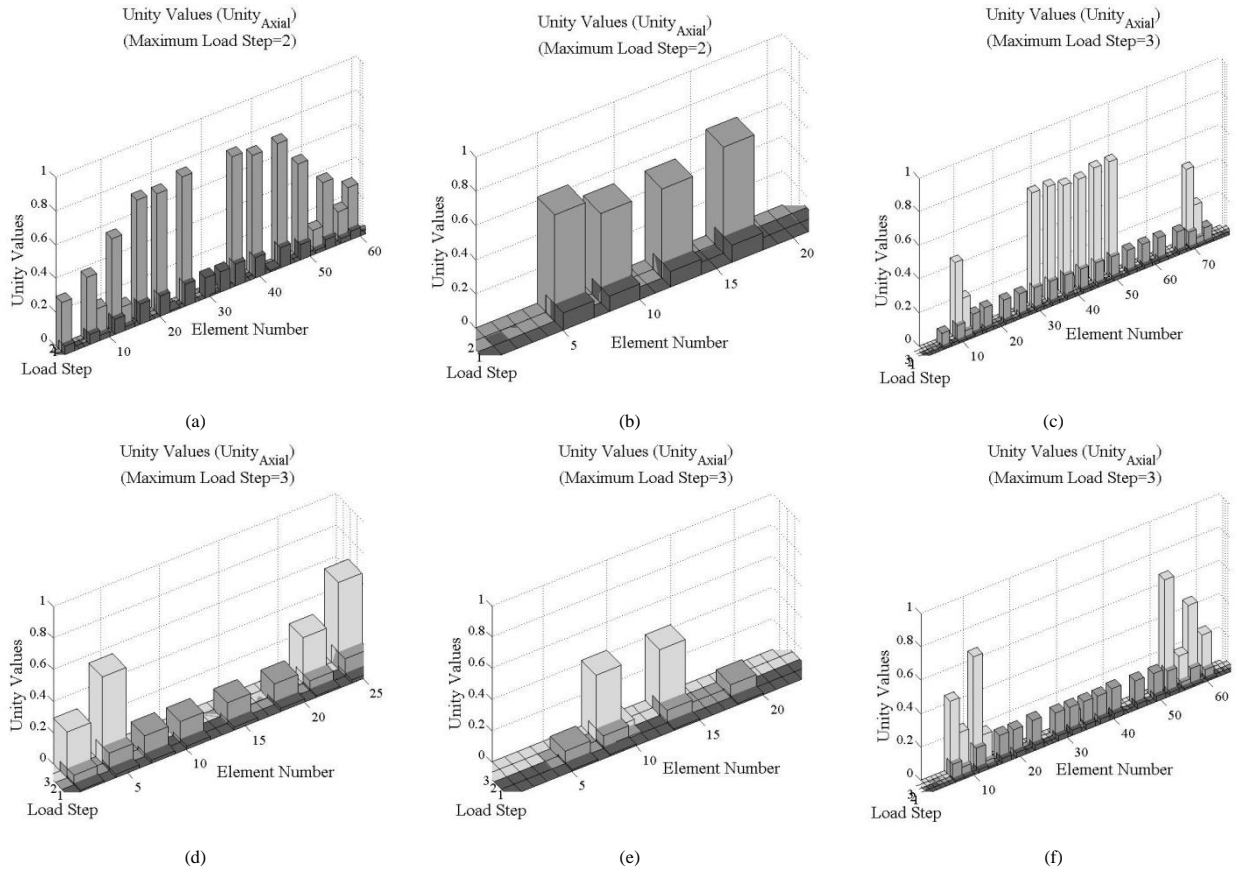


Fig. 8 Variation in The Values of $Unity_{Axial}$ in MRDC for OD1 (a), OD4 (b), OD9 (c), OD10 (d), OD15 (e), OD16 (f) According to Load Steps (see Tables (5-6))

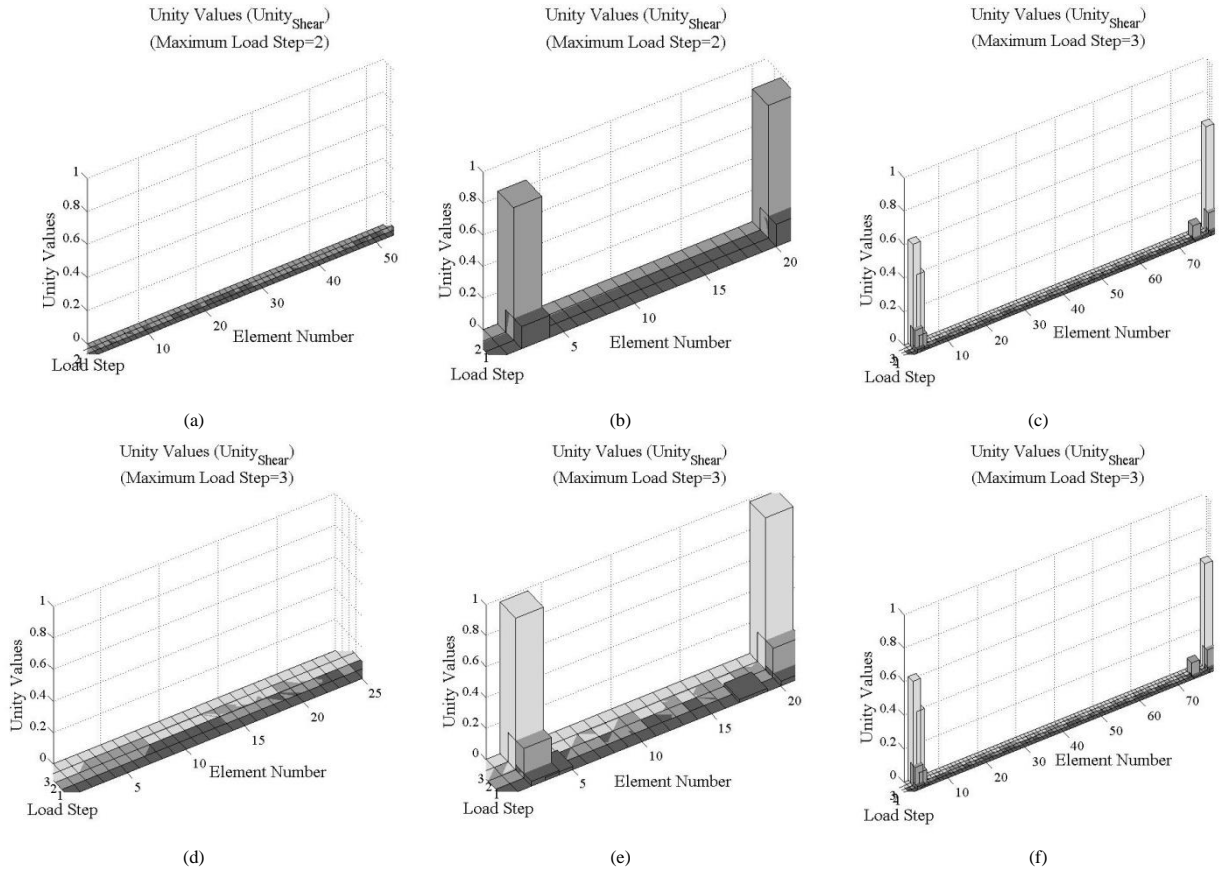


Fig. 9 Variation in The Values of $Unity_{Shear}$ in MRDC for OD3 (a), OD4 (b), OD9 (c), OD10 (d), OD13 (e), OD18 (f) According to Load Steps (see Tables (5-6))

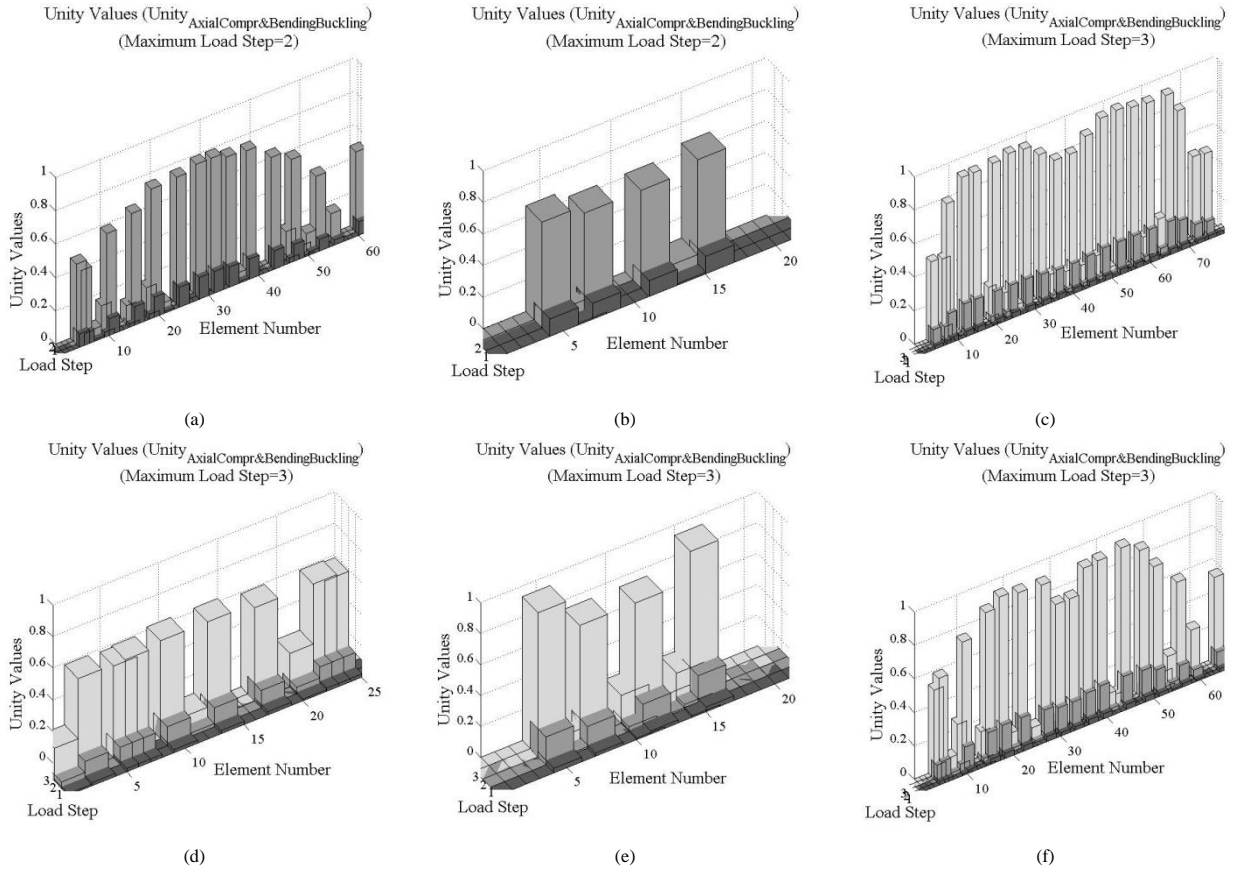


Fig. 10 Variation in The Values of UnityAxialCompression&BendingBuckling in MRDC for OD1 (a), OD4 (b), OD9 (c), OD10 (d), OD13 (e), OD16 (f) According to Load Steps (see Tables (5-6))

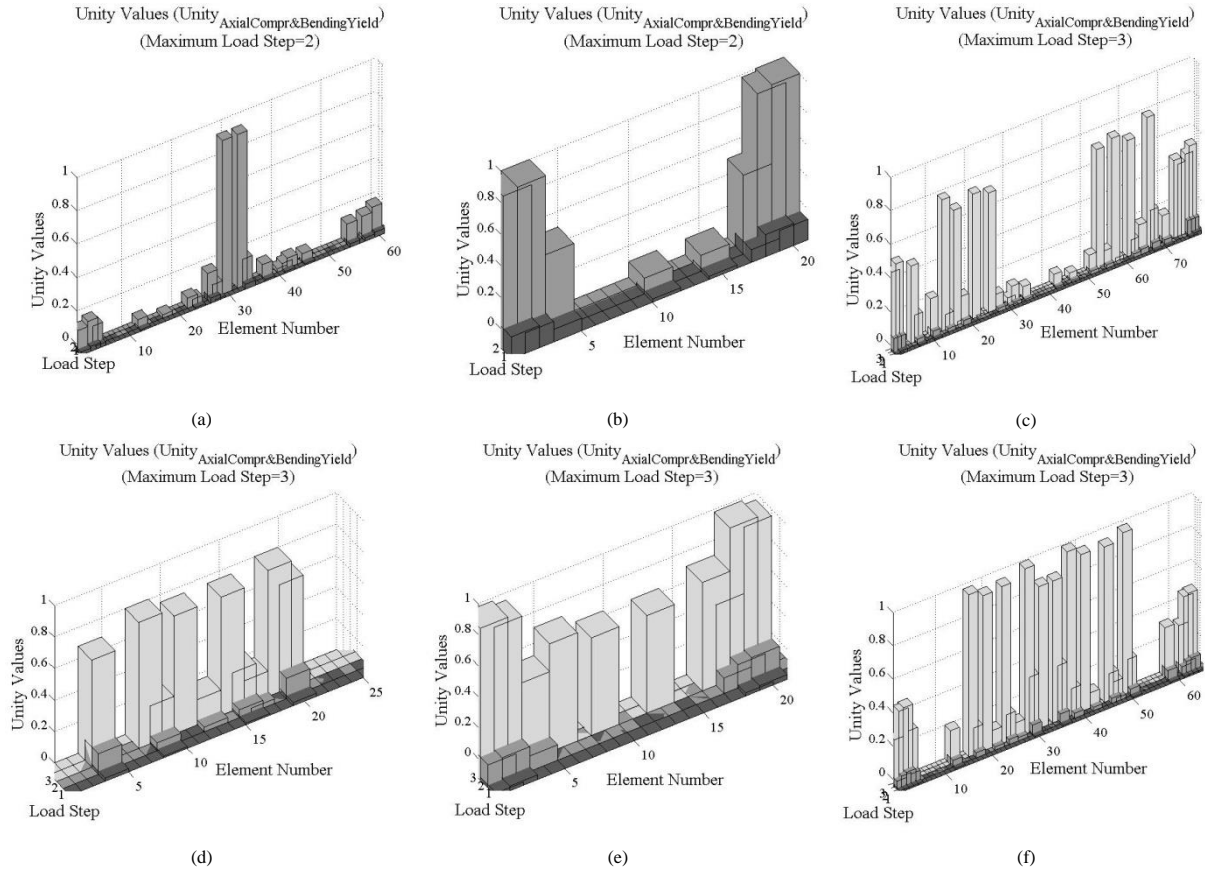


Fig. 11 Variation in The Values of UnityAxialCompression&BendingYield in MRDC for OD1 (a), OD4 (b), OD9 (c), OD10 (d), OD13 (e), OD16 (f) According to Load Steps (see Tables (5-6))

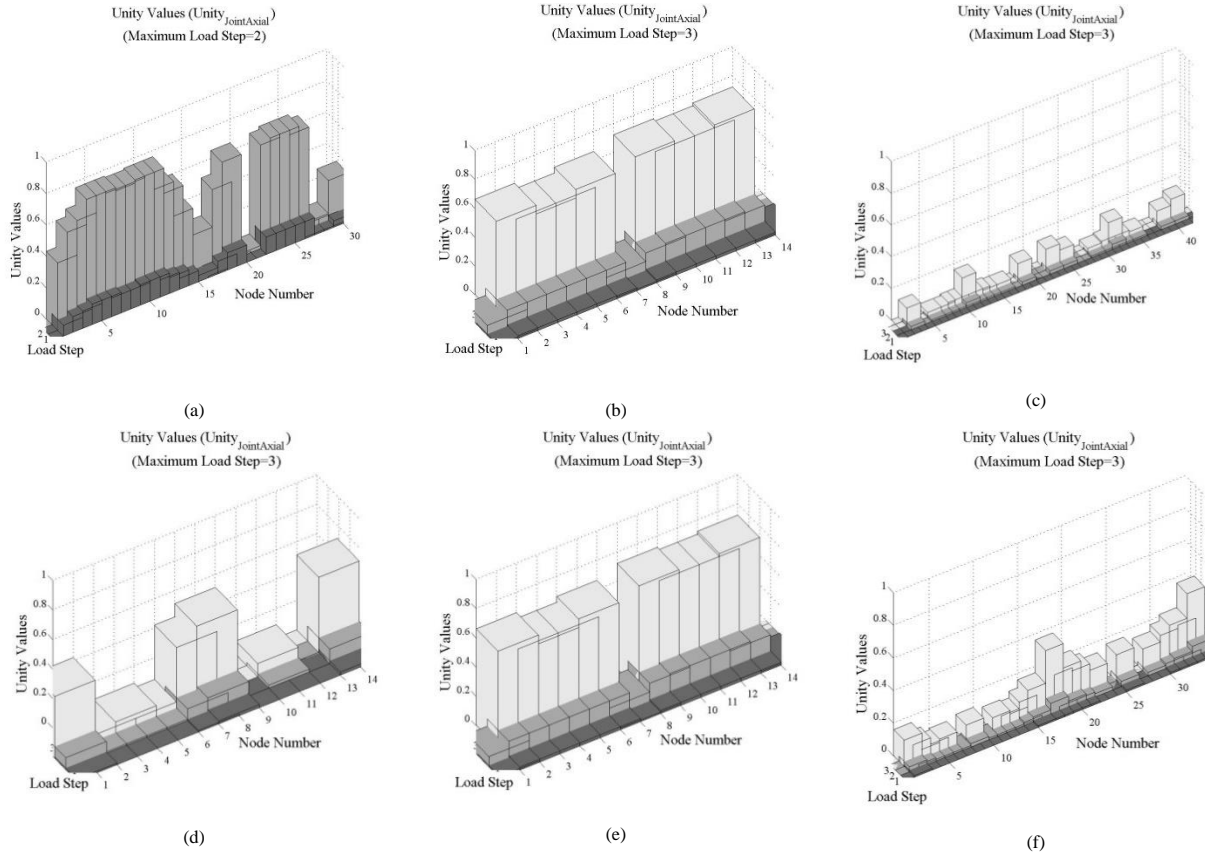


Fig. 12 Variation in The Values of $Unity_{JointAxial}$ in JRDC for OD1 (a), OD6 (b), OD9 (c), OD10 (d), OD15 (e), OD16 (f) According to Load Steps (see Tables (5-6))

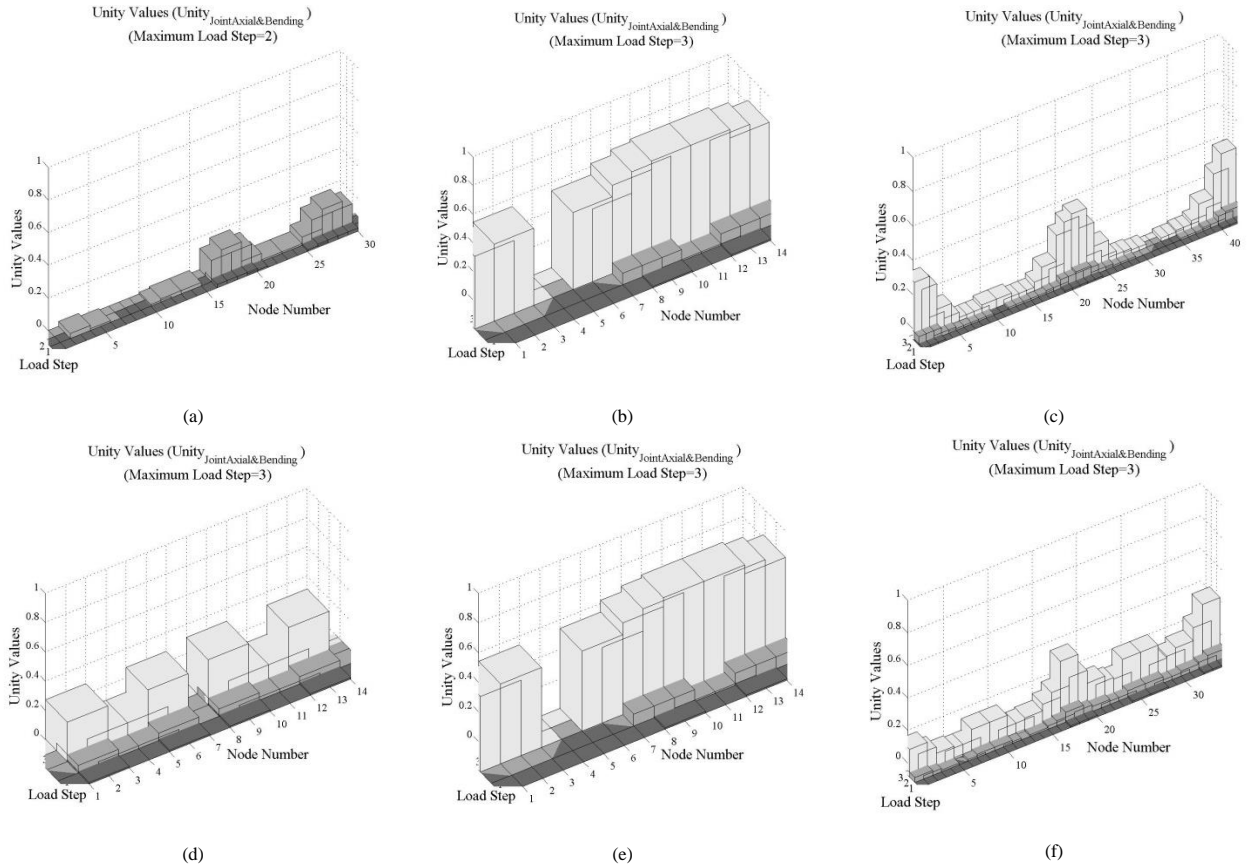


Fig. 13 Variation in The Values of $Unity_{JointAxial\&Bending}$ in JRDC for OD3 (a), OD6 (b), OD9 (c), OD10 (d), OD15 (e), OD16 (f) According to Load Steps (see Tables (5-6))

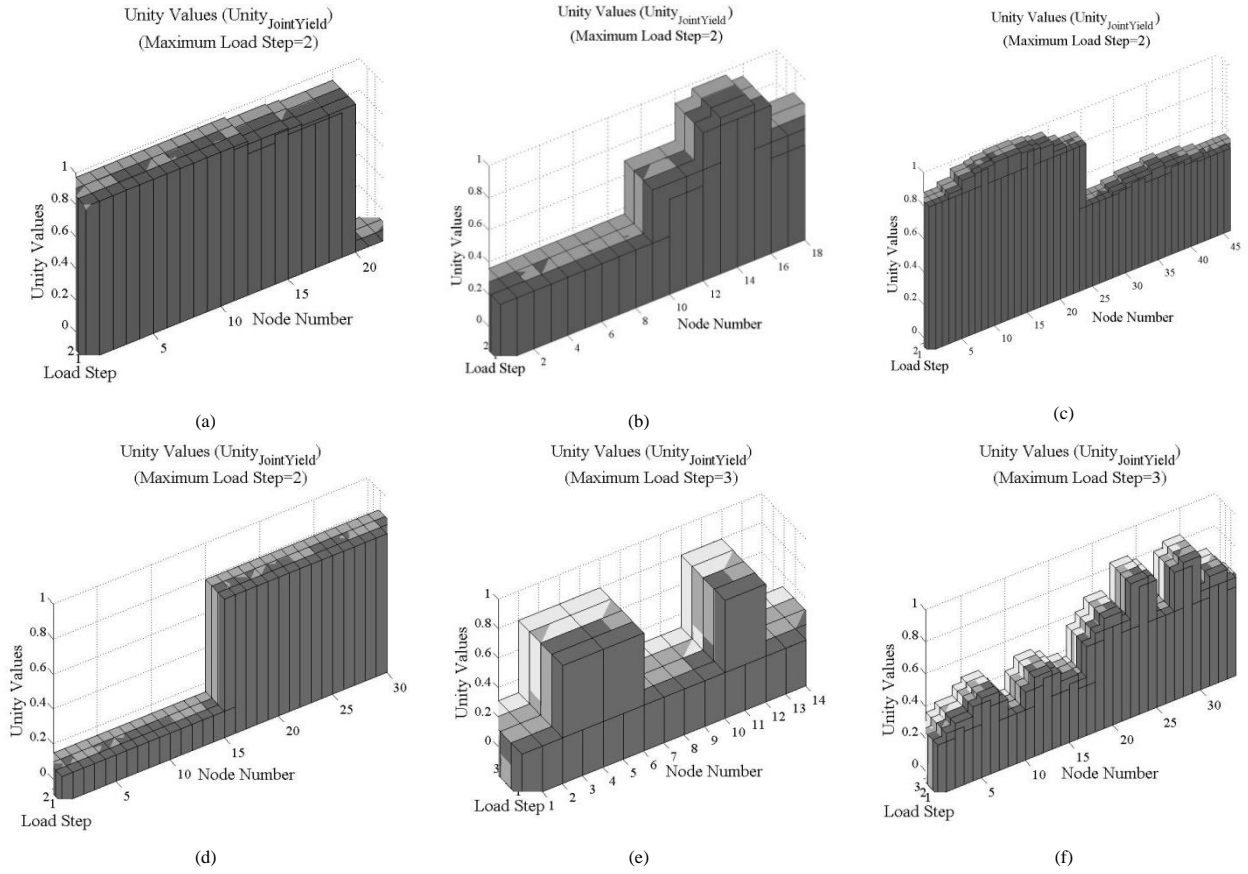


Fig. 14 Variation in The Values of $Unity_{JointYield}$ in JRDC for OD2 (a), OD5 (b), OD8 (c), OD12 (d), OD13 (e), OD16 (f) According to Load Steps (see Tables (5-6))

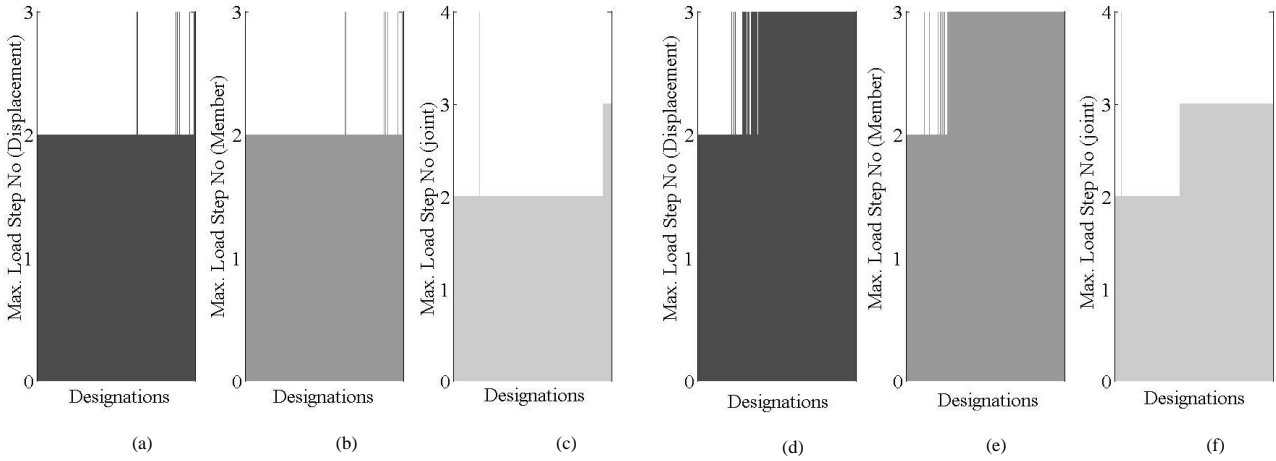


Fig. 15 The Maximum Load Step Numbers (Lattice Girder 2 (a-c) and (Lattice Girder 2 (d-f)) (see Tables (5-6))

5. Conclusion

The design of geometrically nonlinear lattice girders was optimized using the optimization tool named ImpNSGAIL, which was obtained in a way of hybridizing the optimization algorithm named NSGAIL and a neural network approach [17]. The member-related design constraints (MRDC) were taken from the provisions of API RP2A-LRFD specification [28]. In this study, the design complexity for the proposed optimal design approach in Reference [17] is increased thereby including the joint-related design constraints (JRDC) into the current design constraints. Hence, the influence of JRDC on the optimality quality of designs is investigated. Furthermore, the computing efficiencies of both ImpNSGAIL and NSGAIL are also compared by optimizing the benchmark lattice girder and general lattice girder. The following primary observations are summarized as given below:

i) In spite of increasing the design complexity, ImpNSGAIL achieves to obtain the optimal designs with higher load-resistance, economic and serviceability features through its self-adaptive mechanism. However, the simultaneous use of JRDC along with MRDC causes a divergence in the construction cost of tubular lattice girder due to an increase in the entire weight of optimal lattice girder.

ii) It is shown that an inclusion of diagonal members into the framing configuration of automatically generated lattice girder increases the capacities of both member and joint-related strengths. However, the lack of diagonal members in the framing configuration of lattice girder along with an assignment of relatively lower cross-sectional thickness to the members causes to increase the sensitivity in both member and joint-related unities.

iii) It is observed that the joint yield-related design constraint achieves to be the most determinative one among the other joint-related design constraints due to its higher values.

iv) Considering the extreme optimal designs, the solely use of proposed three objective functions, entire weight of lattice girder, its joint displacements and its member forces causes to prevent a tradeoff analysis among these objective functions. But, it is shown that a simultaneous use of these multiple objective functions correspondingly provides both to make a concise and reasonable evaluation of MRDC and JRDC-related design constraints and to obtain optimal lattice girder designs with relatively higher joint and member strength capacities.

Consequently, this challenging optimal design approach achieves to explore the optimal lattice girder designs with higher load-resistance capability thereby increasing the design reliability through the usage of JRDC along with MRDC. Therefore, ImpNSGAIL is recommended to obtain an optimal design configuration for the lattice girder according to a pre-defined spanning length and loading adjustment.

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