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DEVELOPMENT OF A SIMPLIFIED BEAM MODEL FOR TUBULAR JOINTS IN JACKET STRUCTURES

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Abstract

Jacket structures are extensively used to support heavy-weight offshore infrastructure systems. Hence, reliable simulations and designs are vital to facilitate the safe extraction of offshore energy sources, accommodating the gradual transition to green energies. The tubular members of a typical jacket structure, i.e., braces and chords, are usually simulated by either shell or beam elements. However, the latter typically disregard local flexibility contributions at the point of connection that may lead to an overestimated stiffness of the joint. As reported in the literature, the local deformations in the beam models are not negligible, influencing both the static and dynamic performance of the joint and thereby the entire jacket structure. The present paper introduces a simplified method applying a standard beam element in order to account for the joint flexibility providing a low-dimensional finite element model for jacket structures. To this end, a differential evolution optimization algorithm is applied, considering modal parameters as the objective function. The procedure results in obtaining the geometrical and mechanical properties of the simplified beam element introduced herein to model the tubular joints. The investigation of several case studies with different joint types verifies the effectiveness and the application range of the introduced element in modal and static analyses.

Keywords: Tubular joint, Finite Element Model, Optimization, Joint Flexibility, Jacket Structures, Differential Evolution.

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1 INTRODUCTION

Tubular joints refer to the members' connection points of circular hollow sections, extensively used in steel jacket structures and offshore platforms. The behavior of tubular joints must be studied to ensure such systems' safe and reliable design and construction. Using beam tubular (pipe) elements for modeling jacket structures' tubular members (i.e., braces and chords), they are rigidly connected at the nodal points. However, Local Joint Flexibility (LJF) is an intrinsic feature of tubular joints that affects jacket structures' global static and dynamic responses. One of the critical effects concerning LJF is the ovalization as the local deformation of the chord cross section due to large flexibility in the radial direction. The LJF may increase the deflections, redistribute the nominal stresses, reduce the buckling loads, and change the structure's natural frequencies. The analysis of a jacket platform considering LJF results in lower natural frequencies than the model with rigid joints. However, the LJF effects vary with different brace and chord geometry for a given joint shape [1], [2].

Several studies have been dedicated to developing appropriate formulation and parametric equations for LJF with different brace-chord connection shapes based on finite element (FE) analysis and experimental testing. The early works reported parametric equations for tubular T-joints [3] and T-, Y- and K-joints [4], where the braces were subjected only to bending loads. Considering the axial loads, the TY joints were also parameterized compared with experimental results and extended to additional joint types and geometric parameters affecting the LJF [5]. The interaction between braces and the effect of gap length on LJF have been investigated [6]. Despite the advancements found in existing studies, the proposed relationships regarding the LJF highly depend on the joint shape and geometry, loading conditions, structure geometry, and global dynamics [7].

The present study aims to develop a simplified FE submodel based on tubular beam elements with LJF features in the peer shell model. The procedure consists of two FE simulation steps in Abaqus for a given shell model (brace-chord) and a desired beam model connected to a Differential Evolution (DE) optimization step that results in optimal geometry and material properties for the beam. The procedure is straightforward and applicable to different tubular joint shapes, geometry, and loading. Investigating several case studies with various joint forms verifies the introduced element's effectiveness and application range in modal and static analyses.

2 METHODOLOGY

The present work develops a special beam element with LJF features via a combined simulation-optimization process determining geometric and material properties. The steps are demonstrated in Figure 1 and listed in the following.

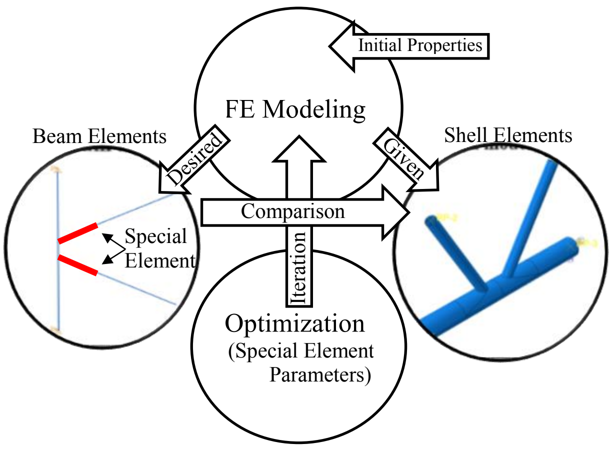

Figure 1: Proposed procedure for developing special beam element with joint flexibility features.

Input: Initial geometric and material properties of the chord-brace
Output: Optimal values for the special beam element's properties (joint) including length, Young's modulus, diameter, thickness (L, E, D, t)
Steps:

1. Simulation of the reference FE model with shell elements, extracting modal parameters.
2. Simulation of the beam FE model within a loop with initial values of the shell model for both brace-chord and special beam elements at the joint locations, extracting modal parameters.
3. Defining the objective function for DE optimization, in terms of natural frequencies and mode shapes with uniform weights for each mode, calculated within the loop in Step 2.
4. Defining the constraint for parameters L, E, D, and t and initial population for DE within the loop in Step 2.
5. Performing initial optimization (few iterations) to modify the weights in Step 3 with respect to the difference between beam and shell models' modal parameters.
6. Running Step 2 in the loop until the convergence of DE with optimal L, E, D, t.

2.1 Special Beam Element Properties

The procedure graphically depicted in Figure 1 starts with creating the FE model of a typical brace-chord assembly with shell elements. In contrast, the peer FE beam model (i.e., rigid joint) does not account for any flexibility at the connection point called LJF. In order to add LJF features to the beam model, the geometry and material properties of a special beam element at the connection point are updated iteratively within a DE optimization process. Figure 2 illustrates some special beam elements for different brace-chord assemblies. Notably, the dimensions of the brace-chord assembly must be appropriate beforehand, so the analysis based on the two FE models (i.e., the shell and the beam with a rigid joint) are remarkably different, and the LJF is considerable. To this end, a comparison is made based on the following ratios:

$$r_k = \frac{K_{Beam}}{K_{Shell}} \tag{1}$$

$$r_\omega = \frac{\omega_{Beam}}{\omega_{Shell}} \tag{2}$$

where K is the lateral stiffness (i.e., force/displacement) and ω is the eigen frequency. Hence, having r_k and r_ω close to 1, it refers to a better match between shell and beam models in terms of static and dynamic behavior, respectively. While the values deviating from unity refer to better case studies (initial geometry and material properties of the brace-chord assembly) for the optimization step. However, after selecting appropriate initial geometry and material properties, in the optimization step in this study, only the eigen frequencies (and mode shapes are) used to assess the fitness since, in contrast to the lateral stiffness, they are not load-dependent.

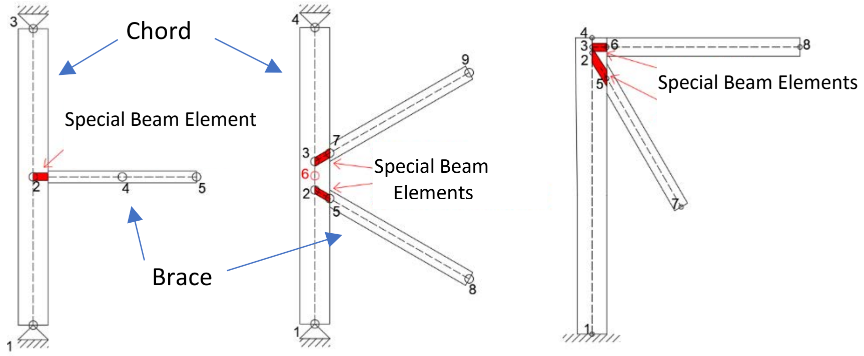

Figure 2: Schematic of special beam elements with joint flexibility for various tubular joints

The parameters to be optimized to define the special joint element are the length (L), Young's modulus of Elasticity (E), the diameter (D), and the thickness (t). These four parameters are referred to each joint element, so for the TY joints eight parameters in total need to be optimized. The number of parameters for the K joint reduces to four due to the symmetric geometry. The initial values for L, E, D, and t are chosen the same for the brace. Then they are constrained by reasonable upper and lower bounds to make the optimization process more efficient.

2.2 Optimization

The implemented DE optimization algorithm finds the global minimum of a multivariate function. The DE algorithm can be considered as a sequence of steps: initialization of the population, evaluation, mutation and recombination, replacement and final evaluation. The difficulty of finding the optimal solution for high dimensional variables can be solved by increasing the population size or increasing the number of iterations [8]. Using the DE algorithm, the parameters L, E, D, and t for each special joint element are found by minimizing two objective functions. One based on the eigenfrequencies:

$$f_\omega(\Delta\omega_1, \Delta\omega_2, \ldots, \Delta\omega_n) \tag{3}$$

where $\Delta\omega_j$ is the difference between the two models eigenfrequency as:

$$\Delta\omega_j = \left|\omega_{j,Shell} - \omega_{j,Beam}\right| \tag{4}$$

The other objective function is based on the mode shapes:

$$f_\phi(e_1, e_2, \ldots, e_n) \tag{5}$$

and

$$e_j = 1 - MAC(\phi_{j,Shell}, \phi_{j,Beam}) \tag{6}$$

Where *MAC* is the Modal Assurance Criterion between two mode shape vectors defined as

$$MAC(\phi_i, \phi_j) = \frac{\left|\phi_i^T . \phi_j\right|^2}{\left|\phi_j\right|^2 . \left|\phi_j\right|^2} \tag{7}$$

The *MAC* values vary from zero to one, indicating the two mode vectors' complete difference and similarity, respectively. Considering the first n modes in the process with weighting coefficients, the total values for Eqs. (4) and (6) to minimize become

$$\Delta\omega_{Total} = \sum_{j=1}^{n} W_j \Delta\omega_j \tag{8}$$

$$e_{Total} = \sum_{j=1}^{n} W_j \Delta e_j \tag{9}$$

where W_j is the weighting coefficient that must be chosen according to each mode's contribution so that $\sum_{j=1}^{n} W_j = 1$. However, the difference between the mode shapes of the beam and shell models is not as much as the frequencies and, hence, Eq. (8) becomes dominant in the optimization.

3 FINITE ELEMENT SIMULATION

The beam FE model is built based on the 2D Bernoulli-Euler beam theory in Abaqus using two-node elements with three DOFs (two translations and one rotation) at each node. The reference shell model is a thin shell element with six DOFs (three translations and three rotations) at each node, considering both in-plane and out-plane deformations. The steel material properties are chosen for the models with Young's modulus of Elasticity equal to 200 GPa and mass density of 7770 kg/m3. Figure 3 exhibits the beam and shell FE models developed in Abaqus for tubular T, K, and TY brace-chord assemblies (or briefly T, K, and TY joints). The two ends of the chord are pinned for T and K joints, and the bottom end of the TY joint is fixed. The chord cross-section and generated meshes for T joint are displayed in Figure 4.

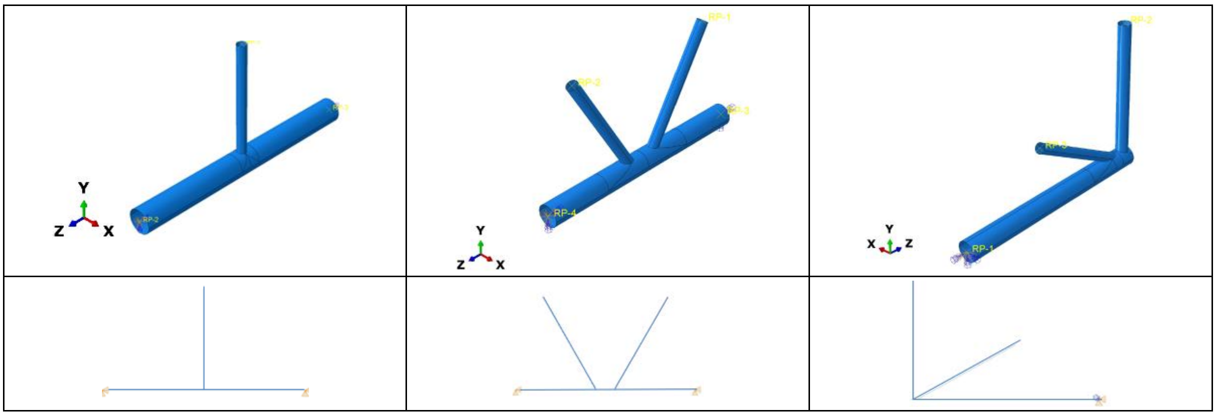

Figure 3: Beam and shell FE model for tubular T-, K- and TY joints

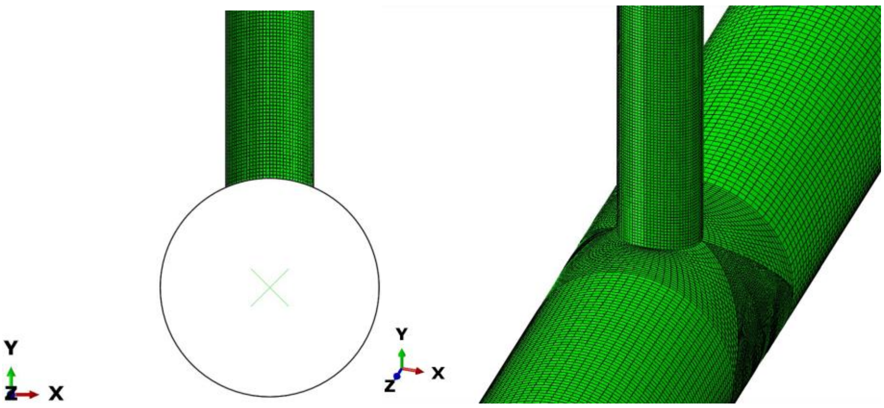

Figure 4: FE model of the T joint in Abaqus shell model with quadratic meshes

In order to find appropriate geometry range for the brace-chord assembly with considerable LJF, several beam and shell models with different geometries have been developed. At this step, the lowest r_k and r_ω introduced in Eqs. (1)-(2) are investigated, indicating the significant difference between the shell and the beam models, and the effectiveness of the optimization process. Figure 5 depicts three types of brace-chord assembly (T, K and TY joints) subjected to two load cases to investigate r_k through the static analysis. The selected dimensions for the brace-chord assembly are presented in Table 1.

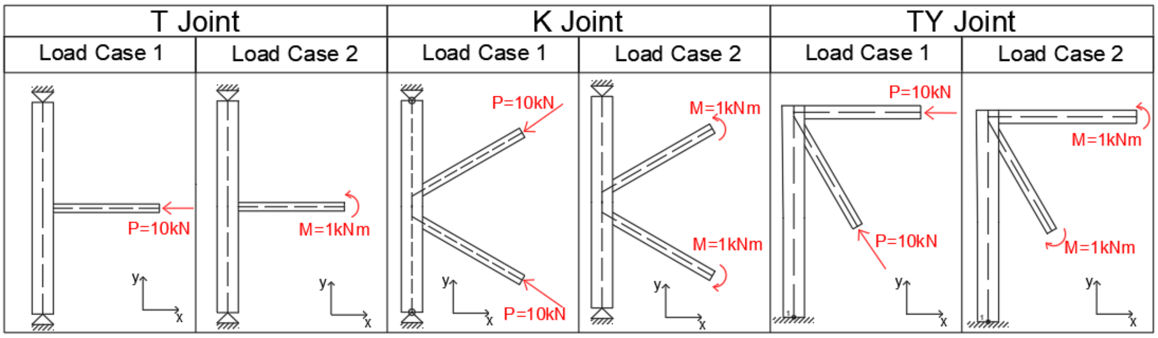

Figure 5: Applied loads to various joints in static analysis

Joint Type	T		K		TY		
Component	Chord	Brace	Chord	Brace	Chord	Brace (Horizontal)	Brace (Skewed)
Length	2.0	1.3	2.0	1.0	2.0	1.3	1.0
Diameter	0.2	0.125	0.2	0.1	0.2	0.125	0.1
Thickness	0.005	0.0045	0.007	0.005	0.005	0.0045	0.0045

Table 1: Dimension of the brace-chord assemblies utilized in the FE simulation (m)

4 RESULTS

4.1 Special beam element for joint modeling

The DE optimization has been performed to find special beam element parameters (E, L, D, t) concerning the red elements highlighted in Figure 2. The special beam element considers the LJF in the shell model of brace-chord assembly with T, K and TY shapes. The first four eigenfrequencies and mode shapes are considered as the objective function, and the parameters are constrained as $1.8\times10^{11} < E < 2.2\times10^{11}$ Pa, $0.1 < L < 0.5$ m, $0.07 < D < 0.13$ m, $0.002 < t < 0.005$ m. The initial guess for them in the optimization process is selected to be identical with the full assembly according to Table 1. Table 2 represents the effectiveness of the optimization process for developing special beam element in the T joint, where *W* indicates the weighting percentage of each mode in four different optimization cases. Additionally, e_{rgd} is the relative error between the shell and rigid beam models' eigenfrequency while e_{opt} is the relative error between the shell and optimized (special beam) models' eigenfrequency.

Optimization Case	1			2			3			4		
Mode	*W*	e_{rgd}	e_{opt}	*W*	e_{rgd}	e_{opt}	*W*	e_{rgd}	e_{opt}	*W*	e_{rgd}	e_{opt}
1st	25	43.10	3.70	40	43.10	0.09	30	43.10	0.13	10	43.10	3.08
2nd	25	3.17	6.59	40	3.17	4.04	60	3.17	3.80	90	3.17	3.79
3rd	25	15.41	0.12	10	15.41	1.98	5	15.41	1.93	5	15.41	1.37
4th	25	15.60	11.0	10	15.60	11.13	5	15.60	11.12	5	15.60	10.96
Total	100	77.3	21.4	100	77.3	17.2	100	77.3	17.0	100	77.3	19.2

Table 2: Percentages of weighting coefficients and eigenfrequency errors for T joints

As seen in Table 2, without special beam element optimization (namely, the rigid joint modelling choice), the error for the 1st fundamental mode is more than 43% and in total becomes more than 77%. Hence, the deviation of the beam model only by disregarding LJF is significant. On the other hand, the use of weights in optimization cases 2 and 3 significantly reduces the error for the 1st and 3rd modes and in total results in 60% percent error reduction. Notably, the 2nd mode error is already low and is not improved by the optimization. As such, the effectiveness of the special beam element in the K and TY shape joints can be seen in Table 3, indicating almost 40% and 80% total error reduction after using the optimized special beam element with LJF.

Type	K			TY		
Mode	W	e_{rgd}	e_{opt}	W	e_{rgd}	e_{opt}
1st	50	15.90	0.10	43	9.30	3.31
2nd	40	18.80	1.84	42	44.30	0.02
3rd	0	1.91	1.91	7.5	13.42	0.01
4th	10	9.91	0.01	7.5	15.94	1.32
Total	100	44.5	1.9	100	83.0	4.7

Table 3: Percentages of weighting coefficients and eigenfrequency errors for K and TY joints

Table 4 represents the optimized parameters of the special beam element with LJF features based on the weights discussed in Table 2 (optimization case 3) and Table 3. The K-joint parameters' variation and convergence are typically plotted versus the optimization iterations in Figure 6. As one can see, D and E are dominant and converge faster than t and L. Hence, the optimization is more sensitive to the length and thickness of the developed joint element and requires the upper-lower bounds for the population generation (i.e., 0.1 m < L < 0.5 m) to be initially adjusted.

Type	T	K	TY	
Component	Horizontal	Two Skewed	Horizontal	Skewed
E ($\times 10^{11}$ Pa)	1.84	2.03	2.14	1.84
L (m)	0.103	0.453	0.478	0.252
D (m)	0.075	0.081	0.062	0.104
t (m)	0.0047	0.0078	0.0078	0.0046

Table 4: Optimized parameters for the special joint elements

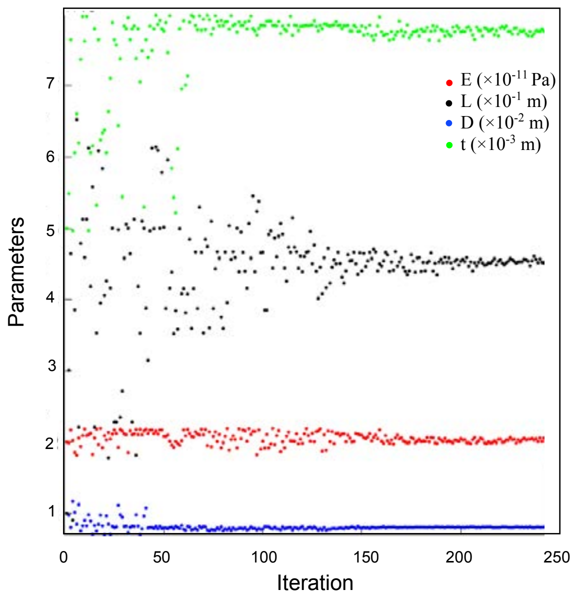

Figure 6: The K-joint parameters' optimization convergence versus the number of iterations

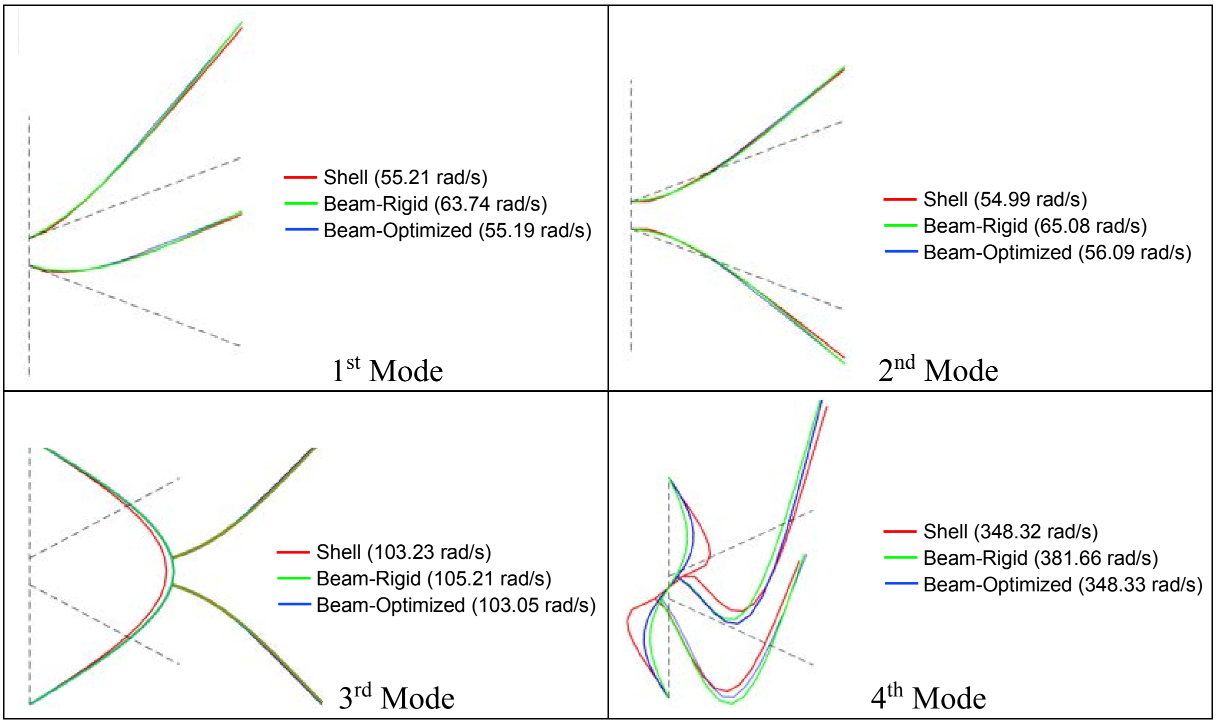

Figure 7: The first four eigenfrequencies and mode shapes of the K-joint FE models

The eigenfrequencies and mode shapes corresponding to the FE beam model with optimized parameters of the special beam element are shown in Figure 7 for the K-joint. The eigenfrequencies are significantly improved in the model with the special joints. In contrast, the mode shapes are not highly different from to model with rigid joints (no special element), except in the 4th mode. Therefore, as mentioned after Eq. (9), the weight of the mode shapes is negligible in the optimization.

The static analysis is also performed with the conditions shown in Figure 5 for two load cases. Table 5 indicates the lateral stiffness r_k (Eqs. (1)) for the rigid model and the optimized model (i.e., with special joint element). The improvement in the T and K joints, especially for Load Case 2, is remarkable. Hence, the special element developed based on the modal parameters as the objective function in the DE optimization, is applicable herein also for the static analysis. It is to be reminded, the deviation of values of r_k from 1, indicates the difference between the shell model and the beam model due to ignoring LJF and ovalization effects in the latter. Figure 8 illustrates the ovalization of the T assembly in the shell model for Load Case 1.

Type	T		K		TY	
	Rigid	Optimized	Rigid	Optimized	Rigid	Optimized
Load Case 1	1.17	1.16	1.31	0.88	1.09	1.06
Load Case 2	1.28	0.98	1.09	0.93	1.50	0.81

Table 5: Lateral stiffness ratio r_k for rigid and special joint elements

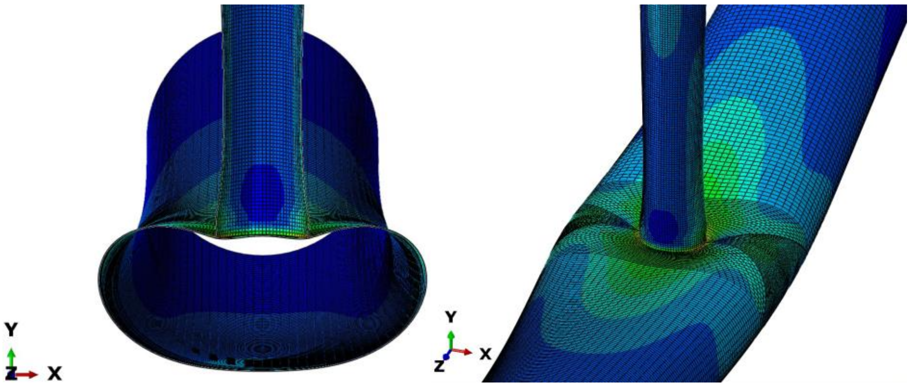

Figure 8: Ovalization of the T-shape shell model subjected to Load Case 1

4.2 Full structure application

The developed special joint elements in specific T, K and TY assemblies, are integrated and applied to a frame structure. Figure 9 displays the geometry of the frame, and the corresponding FE models in Abaqus using beam and shell elements. The thickness of the vertical links (chord) is 0.005m, and the thickness of the horizontal and skewed links is (brace) is 0.0045m.

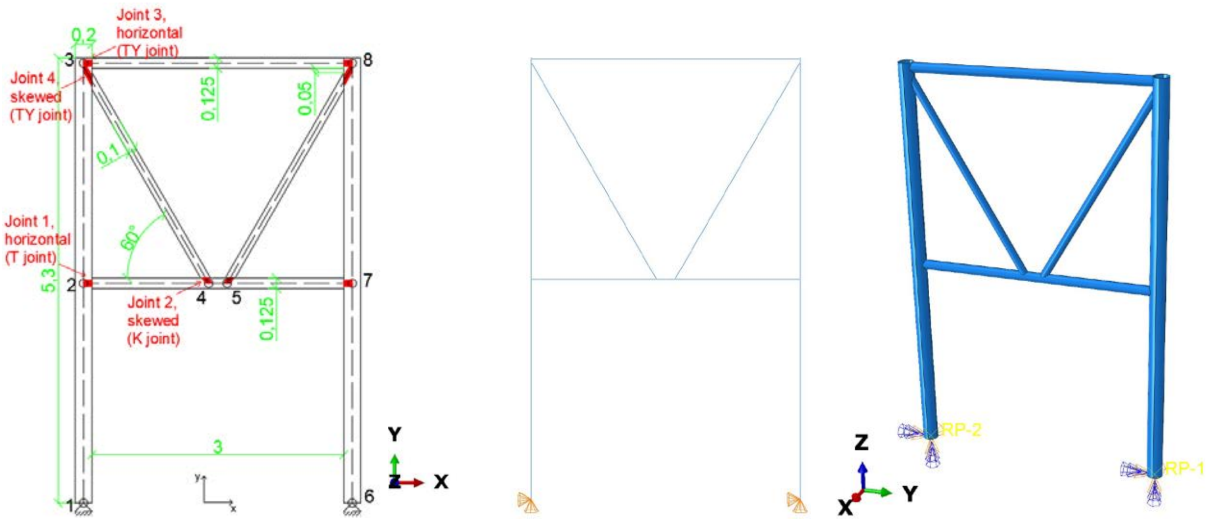

Figure 9: Geometry of the frame with combined joints, and corresponding beam and shell models in Abaqus

The optimization is performed for each joint separately and the obtained parameters (E, L, D, and t) of special joint elements are directly transferred and adopted by the frame structure model. An alternative approach is to perform the optimization considering the full frame beam and simultaneously obtaining parameters for all joints. The results were found to be nearly identical. However, the approach of optimizing the entire structure requires higher computational burden while loses the generality that is associated with the ad-hoc optimization in joint-level and the consequent use of the optiomized joint element to a bigger structure. Table 6 represents the error of the frame's eigenfrequencies modeled by beam elements with rigid joints (e_{rgd}) and optimized beam element with LJF (e_{opt}) compared to the reference shell model.

Mode Number	1st	2nd	3rd	4th	Total
e_{rgd}	5.5	15.1	4.9	11.4	36.9
e_{opt}	1.1	0.3	1.6	0.6	3.7

Table 6: Relative error percentage of frame's eigenfrequencies

As seen in Table 6, the error reduction in the frame's 2nd and 4th frequencies, due to the use of the developed special element with LJF is considerable and, in total, results in more than 30 percent error reduction. The static performance of the model is also evaluated by applying a 1 kN horizontal load to the frame's head at node 3.

Frame FE Model	$x_2 \times 10^{-3}$	$x_3 \times 10^{-3}$	r_k
Shell (reference)	1.94	2.05	-
Beam with Rigid Joint	1.80	1.90	1.08
Beam with special Joint	1.92	2.01	1.02

Table 7: Frame's displacement along x axis at nodes 2 and 3 and stiffness ratio r_k

Table 7 displays the displacement of typical nodes 2 and 3 of the frame and the concerning lateral stiffness ratio r_k. Despite the insignificant difference between the rigid joint and shell model under the given static load, 7% improvement is seen for using the special beam with LJF.

5 CONCLUSIONS

The study aims to develop a simplified submodel that considers the tubular local joint flexibility. The latter can be captured by a shell model of a jacket structure but commonly waived by a simplified beam model with a rigid connections. To reach the goal of this study, a simplified beam is introduced by optimizing a special beam element' geometric and material properties within a differential evolution algorithm. The main conclusions of this research work are summarized below:

- Implementing the procedure for various tubular joint assemblies results in acceptable accuracy and effectiveness of the developed beam element to capture the joint flexibility. However, higher accuracy requires considering other element parameters and extending the search bounds in the optimization process.
- The joint's eigenfrequencies and mode shapes were selected as the objective function since they are independent from the loading conditions. However, the evaluation of the refined submodels subjected to static loads indicates improvements in the response and lateral stiffness.
- The main difference between the mode shapes of the beam and shell model is due to the fact that the shell model's local effects do not appear in the beam model's lower modes. Therefore, the contribution and weight of the mode shapes in the optimization was found to be lower than the eigenfrequencies.
- Substituting simplified beam elements of different joint types in a frame structure indicates both static and dynamic improvements. The latter highlights the capability of such an element to be locally and separately developed and later assembled within large-scale jacket structures with multiple joints.
- The study needs more in-depth investigation to generalize the idea of developing 3D beam joint elements by geometric parametrization, considering nonlinear features, a wider variety of joints, and additional loading conditions.

ACKNOWLEDGEMENTS

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