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*Research Article*

# Blast Demolition Study of Guyed Masts

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Demolition of guyed masts is usually carried out by cutting down some of the supporting guy cables using an explosive in such a way that the mast can fall into the desired direction. Without the cable supports, guyed tubular masts are very slender structures which are susceptible to local buckling based on the internal force distribution. If this local buckling occurs at the early stage of the demolition processes, it can cause uncertainty in the failure mechanism. The risk of undesirable demolition outcome due to this uncertainty can be mitigated by using controlled detonation setups. In this paper, a sensitivity analysis is presented using a case study to determine the influence of the explosive detonation time on the collapse development and pattern of the guyed mast. Then, the results of the sensitivity analysis are systematically categorized using cluster analysis to show possible types of collapse regimes which can be used to setup a controlled demolition scheme.

## 1. Introduction

Guyed masts that are at the final stage of their design lifetime and no longer required for any purpose due to advancements in technology need to be safely and economically demolished. Blast demolition is an efficient method compared to conventional demolition techniques due to the short duration of the demolition process and cost efficiency [1]. Here, it is vital to choose and design a controlled blast demolition setup in order to avoid unsafe situations which may lead to an unexpected collapse regime with undesirable extension of debris areas or an incomplete collapse which has to be removed by an expensive mechanical procedure.

There are a number of investigations that focused on blast demolition of complex large-scale structures [2–4] and blast folding of chimneys [5] based on experimental and analytical methods. On the contrary, researches in the area of mitigation of hazardous structural collapses due to extreme loads such as explosion, impact, and earthquake have contributed towards a better understanding and control of structural collapse mechanisms. These works identified as progressive collapse [6, 7] were carried out particularly on steel structures [8–11] and reinforced concrete framed structures [12–16].

However, when it comes to demolition of guyed tubular masts, there are almost no studies about their collapse mechanisms. Up to now, blast demolition of guyed masts has been typically carried out by experienced explosive demolition experts without any detailed technical investigation in such a way that some of the guy cables were cut using explosives so that the mast can fall into one direction. Even though this approach to demolish guyed masts seems to be successful for some cases, there are always risks involved. In order to avoid or reduce these risks, it is crucial to perform a study of the influencing parameters using numerical simulations of the blast demolition process. This scientific approach makes it possible to determine the optimum position and timing setup of the explosives, which are needed to have the desirable collapse strategy.

Guyed tubular masts in their statically stable position are laterally restrained by cables, which can be considered as intermediate supports. Removing these cables during demolition creates a change in the internal force distribution of the mast and results in a tall and extremely slender beam that is only supported by a hinge at the base. Such a system is not only unstable but also susceptible to local buckling due to a bending moment generated by inertia forces during the falling process. Determining the location and timing of such a buckling during the demolition process can avoid an undesired demolition outcome. Using an appropriate numerical model of the guyed mast in conjunction with sensitivity and cluster analyses, it is possible to predict all possible outcomes of the demolition with respect to the design parameters.

## 2. Case Study

To demonstrate the methods and procedures that can be used to identify an appropriate blast setup, a demolished guyed mast is used in this paper. The total height of this guyed mast above ground level was almost 240 m, but the mast itself was resting on the roof of a 6.20 m high building. It had a circular hollow cross section with an inner diameter of 1.48 m. Up to a height of about 130 m, the wall thickness was 11 mm, and above it measures 9 mm. Wall thinning due to corrosion was not observed since it was regularly maintained. The mast was anchored by three sets of cables in three directions. All this information was available from design drawings and reports. The mast was demolished in 2013 by cutting the two sets of cables at the same time as shown in Figure 1.

The falling direction was chosen such that the second antenna mast and buildings in the vicinity would not be damaged during the demolition. It was intended that the mast falls like a tree straight into the direction of the cables that were not cut. However, as indicated in the overlay Figure 2, the mast buckled in an early phase of falling causing the upper part of the mast to fold back. Fortunately, neighbouring buildings were not damaged.

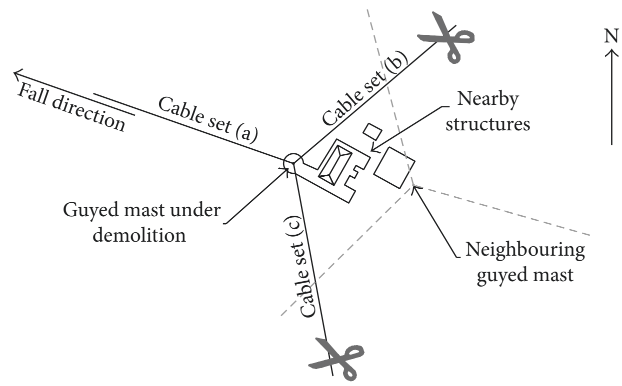


Figure 1: Site layout.

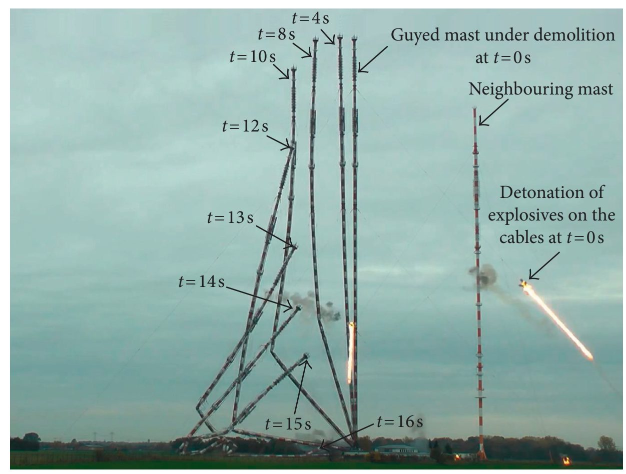


Figure 2: Demolition of guyed antenna mast in 2013.

## 3. Numerical Simulation Model

Realistic simulation of the entire complex dynamic process of guyed mast demolition by means of controlled explosive detonation is one of the most important steps towards understanding the behaviour of the structure and to foresee the problems which should be mitigated during the actual blast demolition. The simulation of guyed mast demolition is a transient dynamic problem with large deformations and rotations involving geometrical and physical nonlinear behaviour, contact, and impact conditions. One appropriate approach to solve this problem is using an explicit finite element method [17] which uses a very small time step to determine the acceleration of a moving system due to applied external forces and gravity. Here, the computation of the accelerations in the following equation for each time increment $i$ can be optimized by using a lumped mass matrix $\mathbf{M}$ which simplifies the computation of its inverse:

$$\ddot{u}_i = \mathbf{M}^{-1} F_i, \tag{1}$$

where $F_i$ represent the summation of internal and external forces. The internal element forces which include all nonlinearities as well as contact conditions are calculated by the formulation built in the element and material models according to [18]. In explicit time integration methods, the solution at time step $t_{i+1}$ depends only upon quantities at time instant $t_i$. Here, a central difference method is used to approximate the velocities and accelerations at $t_i$:

$$\dot{u}_i = \frac{u_{i+1} - u_{i-1}}{2\Delta t}, \tag{2}$$

$$\ddot{u}_i = \frac{\left(\dot{u}_{i+(1/2)} - \dot{u}_{i-(1/2)}\right)}{(\Delta t)} = \frac{u_{i+1} - 2u_i + u_{i-1}}{(\Delta t)^2}, \tag{3}$$

where $\dot{u}_{i+(1/2)} = (u_{i+1} - u_i)/\Delta t$ and $\dot{u}_{i-(1/2)} = (u_i - u_{i-1})/\Delta t$.

From (2) and (3), the displacement can be derived as follows:

$$\begin{aligned} \dot{u}_{i+(1/2)} &= \dot{u}_{i-(1/2)} + \ddot{u}_i \Delta t, \\ u_{i+1} &= u_i + \dot{u}_{i+(1/2)} \Delta t. \end{aligned} \tag{4}$$

For stability reason, the time step allowed in this method should be less than or equal to the critical time step $\Delta t_{cr}$ [19] as given in the following equation, where $T_n$ is the shortest period of the finite element assemblage with $n$ degrees of freedom:

$$\Delta t \leq \Delta t_{cr} = \frac{T_n}{\pi}. \tag{5}$$

The finite element analysis (FEM) presented in this paper is conducted using explicit time integration implemented in LS-DYNA [20].

The shaft of the mast was modelled using 6441 4-node shell elements based on Reissner–Mindlin kinematic assumptions

[21] and with an average square mesh size of 45 cm while the cables were represented by 400 beam elements with an average mesh size of 4 m as shown in Figure 3. Based on a respective parametric study, further resolution of the mesh size did not make a significant difference on the result of the general collapse simulation. To approximate the ground surface, a rigid surface has been introduced. The steel pipe section with a yield stress of 250 MPa and failure strain of 0.2 for eroding elements is modelled using an elastic-plastic material model with kinematic hardening [22]. Here, an effect of high strain rates on the material behaviour is not considered since the blast loading is only applied to the cables.

The computation of the model was performed on *Intel Xeon E5-2650 v2* using the MPP version of LS-DYNA on 4 processors. The average computational time for a computed time of 20 seconds, which is the time needed to complete the demolition processes, was about 50 minutes with a time step size of approximately $1.80 \times 10^{-5}$ seconds (1, 090, 630 time steps).

## 4. Sensitivity Analysis

The outcome of blast demolition of guyed masts depends on several parameters involved in the process. In the preliminary parameter study, uncertainties of input parameters such as mass distribution of the mast and prestress in the cables did not show a significant influence on the demolition process. Here, the most important input parameters are the time of explosive detonation (ToED) for the cables which determines the fall regime of the guyed mast. All possible outcomes of the demolition process for the selected range of ToED can be realized using a sensitivity analysis [23]. To identify from a simulation if the mast has fallen down into the specified debris area and according to the collapse regime, the resultant horizontal displacement of the mast's tip and the time when the first buckling occurred were selected as the output parameters, respectively.

For the global sensitivity analysis, two hundred samples for different ToED were generated by means of a Latin hypercube sampling algorithm [24, 25]. The predefined limits for the parameters are given in Table 1. In all simulations, the upper level cable is cut at the beginning of the demolition ($t = 0$ s). The effect of the blast loading during the demolition is neglected since the small explosives used to cut the cables with an average diameter of 35 mm are located at the base of the cables and do not affect the collapse of the mast. Therefore, a death option at the support of the cables was applied to simulate the cutting process. For each sample set of parameters, a numerical simulation of the complete demolition process has been performed. Based on the results, a respective response surface was generated by means of a moving least squares (MLS) approximation [26]. In the MLS approximation, a local character of the regression is obtained by introducing position-dependent radial weighting functions. An arbitrary function $f(x)$ can be approximated by the following equation [27]:

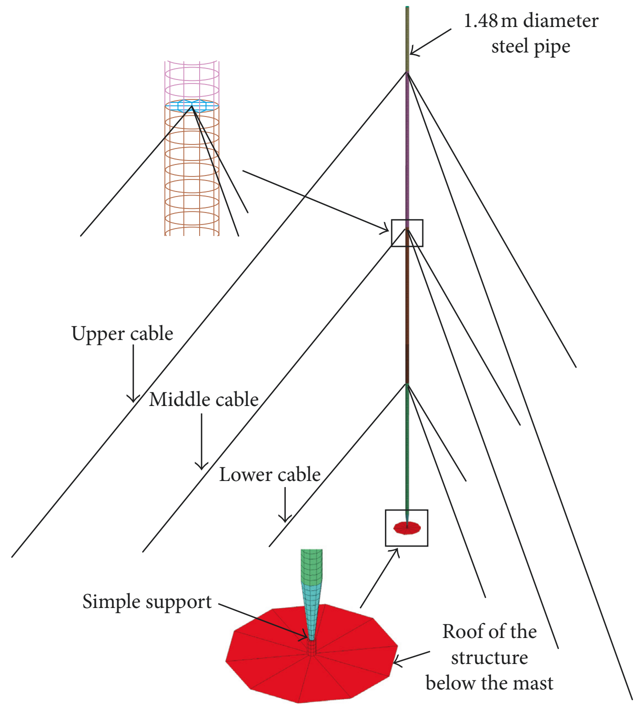


Figure 3: Overview of the FEM model in LS-DYNA.

Table 1: Input parameters considered.

| Input parameter | Range (s) |
|---|---|
| ToED for middle cable | 0 to 6 |
| ToED for lower cable | 0 to 8 |

$$\hat{f}(x) = \sum_{i=1}^{n} p_i(x) a_i(x) = p^T(x) a(x), \quad (6)$$

where $p_i(x), i = 1, 2, \ldots, n$, are the basis functions, $n$ is the number of terms in basis functions, and $a_i(x)$ are the respective coefficients. The basis function was defined as a quadratic polynomial function $p^T(x) = [1, x, y, x^2, xy, y^2]$. The coefficients were determined by a weighted least squares method minimizing the $L^2$-norm error $L_W$:

$$L_W = [Pa(x) - f]^T W [Pa(x) - f], \quad (7)$$

with respect to the unknown coefficients $a(x)$ yielding

$$\frac{\partial L_W}{\partial a(x)} = 0 \longrightarrow a(x) = \left[P^T W P\right]^{-1} \left[P^T W\right] f, \quad (8)$$

where $a(x)$ are the moving coefficients and $\mathbf{W}(x)$ is the diagonal matrix for $m$ given nodes:

$$\mathbf{W}(x) = \operatorname{diag}(w(d_1), \ldots, w(d_m)). \quad (9)$$

The weighting function value of a node $i$ at an interpolation point $x$ is introduced by the following regularized formulation [28]:

$$w_R(d_i) = \frac{\overline{w}_R(d_i)}{\sum_{j=1}^{m} \overline{w}_R(d_j)},$$

$$\overline{w}_R(d) = \begin{cases} \dfrac{\left((d/D)^2 + \varepsilon\right)^{-2} - (1+\varepsilon)^{-2}}{\varepsilon^{-2} - (1+\varepsilon)^{-2}}, & d \le D,\ \varepsilon \ll 1, \\ 0, & d > D, \end{cases} \quad (10)$$

where $d = \|x - x_I\|$ is the distance between the interpolation point and the supporting point and $D$ is the influence radius which is constant or dependent on the position of $x$. The regularization parameter $\varepsilon$ has to be very small for higher accuracy, but it has to be larger than the square root of the machine precision to avoid numerical problems. Finally, substituting (8) into (6) yields the MLS approximation as follows:

$$\hat{f}(x) = p^T(x)\left[P^T W P\right]^{-1}\left[P^T W\right] f. \quad (11)$$

In Figures 4 and 5, the MLS approximations for the output parameters of the tip resultant displacement and time of buckling with respect to the variation of the input parameters are shown.

Here, the plateau region around 240m of tip displacement in Figure 4 indicates that the mast falls without folding since the local buckling occurs at the late stage of the demolition processes as shown in the response surface approximation of the time of first buckling (Figure 5). Using a cluster analysis, these results are further classified into different types of collapse regimes within the predefined time setups.

## 5. Cluster Analysis

Cluster analysis is a grouping of objects or samples based on a given criterion for pattern recognition. Lists of objects belonging to the same group are called clusters. The sample points from the sensitivity analysis, which are representing different collapse regimes for the respective setup of ToED, can be clustered based on the folding mechanism or the fall regime of the guyed mast. In order to compare the folding type of the guyed mast for each sample, the displacement of the mast throughout the height was collected at the time of the first buckling (Figure 5). Then, the collected displacement vectors forming each sample are quantitatively compared to each other using the modal assurance criterion (MAC) [29], and the ones which show largest MAC value (closest to one) are clustered together. The MAC value is calculated as the normalized scalar product of the two sets of vectors $\{\varphi_A\}$ and $\{\varphi_X\}$. The resulting scalars are arranged into the MAC matrix as follows:

$$\mathrm{MAC}(A, X) = \frac{\left|\{\varphi_A\}^T\{\varphi_X\}\right|^2}{\left(\{\varphi_A\}^T\{\varphi_A\}\right)\left(\{\varphi_X\}^T\{\varphi_X\}\right)}. \quad (12)$$

In Figure 6, the samples which are similar in their collapse scheme are clustered together and shown by the same color. The results of the cluster analysis clearly show different regions of collapse scheme in the input parameter space which will help us to select an appropriate combination of ToED for the desired type of demolition regime shown in Figure 7. The case of *Regime A* is similar to the actual

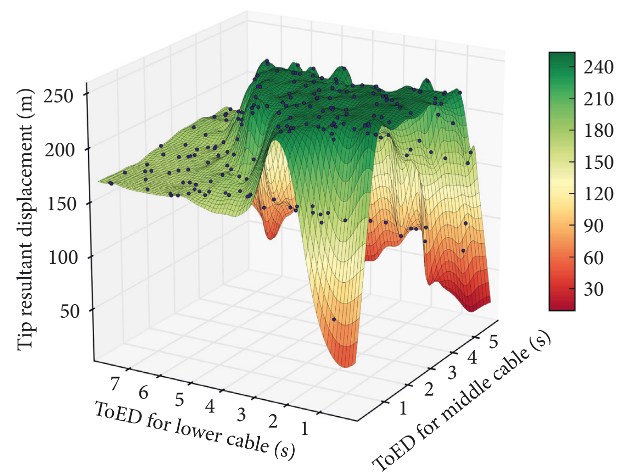


FIGURE 4: MLS approximation of tip resultant horizontal displacement.

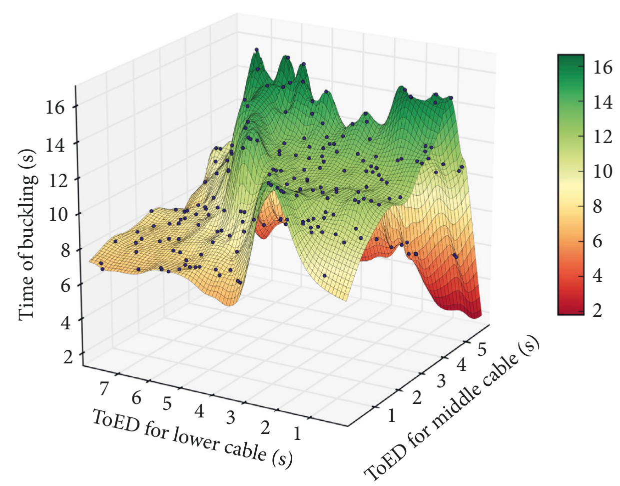


FIGURE 5: MLS approximation of time of first buckling.

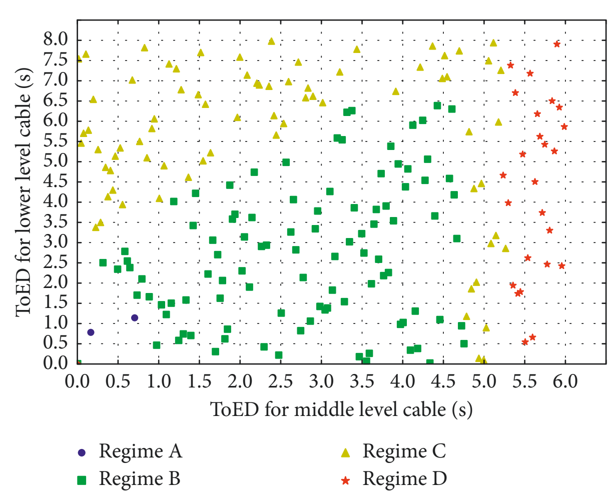


FIGURE 6: Results of cluster analysis.

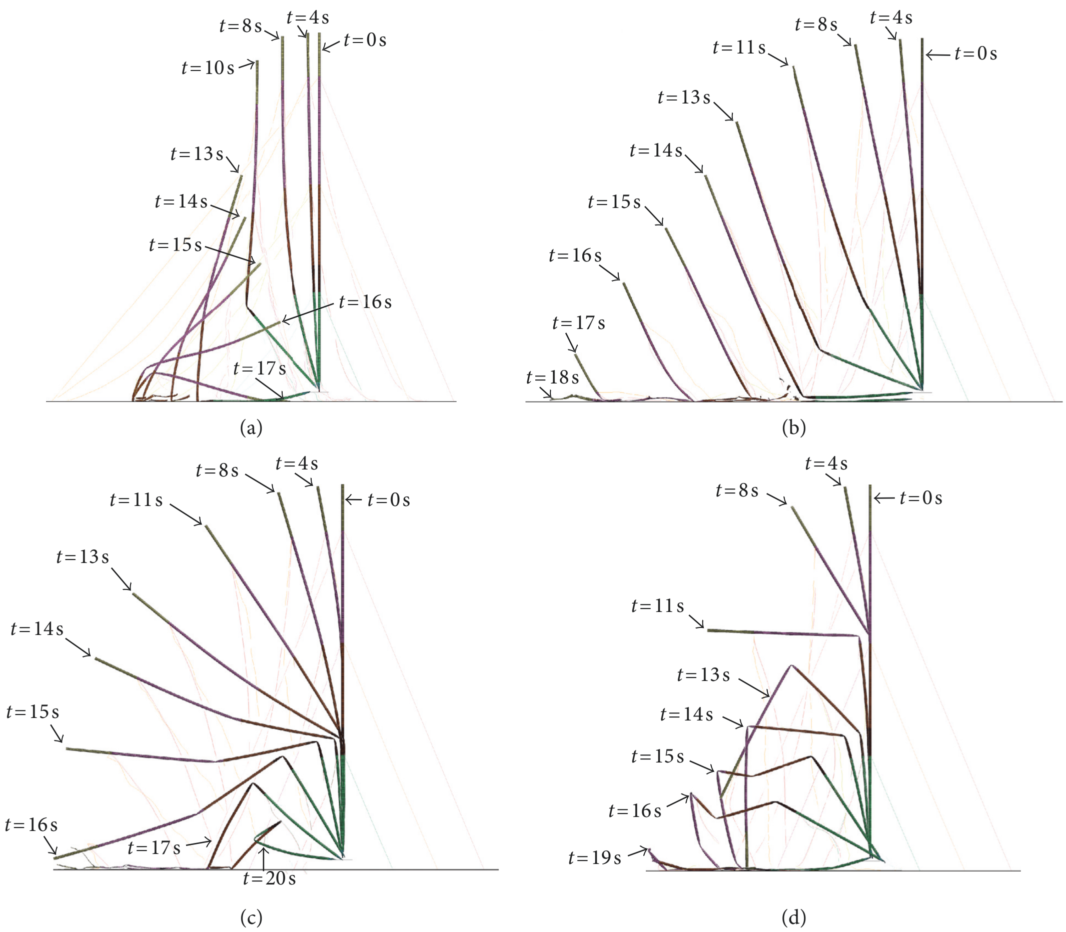


Figure 7: Types of fall regimes: (a) Regime A, (b) Regime B, (c) Regime C, and (d) Regime D.

demolition of the guyed mast shown in Figure 2 since the ToED for middle and lower cables is close to zero. This similarity of result validates the numerical model used to simulate the demolition of the guyed mast.

Based on the site layout shown in Figure 1, the best demolition scheme for the case study would be any detonation sequence well within the boundaries of *Regime B* in which the mast falls in the desired direction like a tree without any imminent damage to the nearby structures. All the other regimes are not suitable because of the following:

(i) *Regime A* has a high probability of the mast tip hitting the nearby structure and an incomplete collapse for a small section of the guyed mast as shown in Figure 8.

(ii) *Regime C* has an even higher probability of incomplete collapse since the triangular mast configuration at $t = 17$ s can deeply penetrate into the ground during impact depending on the soil condition of the demolition site. In this case, the remaining parts of the guyed mast must be removed by an expensive procedure.

(iii) *Regime D* can cause damage to the nearby structures since the base of the mast slides opposite to the fall direction.

Figure 8: Guyed mast debris section partly penetrated into the ground.

## 6. Conclusion

The objective of this study was to assess the influence of specific input parameters on the outcome of a guyed mast's demolition process based on a numerical simulation. The case study presented in this paper shows an approach to conduct a controlled explosive demolition for cutting the support cables. According to the sensitivity analysis, the change in the input parameters, such as ToED, highly influences the result of the demolition process. The two output parameters selected for this case study show the behaviour of the mast during the demolition. As the objective is to prevent damage of structures in the neighbourhood, it is recommended to search for a detonation sequence that leads to a maximal horizontal displacement of the masts tip at the end of the demolition process. This detonation sequence is clearly shown on the sensitivity analysis (Figure 4) by the plateau region at about 240 m; likewise to achieve this horizontal displacement, the time of the first buckling should be as late as possible which is above 12 s (Figure 5).

In general, the availability of all possible types of collapse regime from the cluster analysis facilitates the choice of a safe explosive time setup for the cables by selecting an appropriate parameter set which results in a collapse of the mast with a minimal risk for structures in the vicinity. This research can also be further extended to demolition of guyed lattice masts which are usually much stiffer than guyed tubular mast. In these cases, local failure can occur not only due to buckling but also due to other reasons such as the exceedance of the joint strength.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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