Journal of Constructional Steel Research 123 (2016) 31–40

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Progressive collapse analysis of power transmission towers

Behrouz Asgarian [a], Soheil Dadras Eslamlou [a,*], Arash E. Zaghi [b], Masoud Mehr [b]

[a] Department of Civil Engineering, K. N. Toosi University of Technology, Tehran, Iran
[b] Department of Civil and Environmental Engineering, University of Connecticut, Storrs, CT, USA

ARTICLE INFO

Article history:
Received 9 July 2015
Received in revised form 23 March 2016
Accepted 21 April 2016
Available online 6 May 2016

Keywords:
Progressive collapse
Lattice towers
Capacity-to-demand ratio
Pushdown analysis
Overload factor

ABSTRACT

Lattice transmission towers are critical components of power infrastructures. Collapse of a transmission tower may cause major economic and social impacts. The present study aims to evaluate the progressive collapse vulnerability of a lattice tower in a 400 kV power transmission line. The load increase factors (IF) after an instantaneous element removal are determined for application in static analyses and for design purpose. The capacity-to-demand ratios (C/D) are proposed to identify critical members after different removal scenarios. This proposed parameter is examined by comparison with Overload Factor (OF) from pushdown analysis. In addition, the pushdown analysis is used to determine the remaining capacity of the structure after removing an element. It is found that tower may resist progressive collapse because of the possible alternative load paths. It is also observed that the studied structure has less susceptibility to progressive collapse in scenarios of element removal at higher elevations.

1. Introduction

Collapse is defined as a consecutive failure of structural elements that eventually leads to failure of the entire system or a large part of it [1]. The following may trigger progressive collapse: 1) design or construction errors, 2) heavy object impact, 3) elevated temperatures, 4) explosion, 5) extreme and accidental loads, 6) inadequate connection, among several others [2]. The continued growth of communities demands the development and expansion of power plants and power distribution networks. Reliable and uninterrupted operation of power transmission lines is crucial. Lattice structures are typically used to carry the weight of heavy conductors. A better understanding of the structural response of lattice towers under extreme loading is necessary for improving the safety and security of power lines. To this end, the impact of element failure on the response of the entire system and the failure modes should be realized.

To reduce the power loss, the voltage is increased; hence the conductors are large diameter and heavy cables. Due to the considerable weight and span of the conductors, rupture of one or multiple conductors results in significant unbalanced loads on the structure that may lead to failure of elements and possibly structural collapse of the transmission tower. The overload due to heavy ice accumulation on conductors is another cause of failure.

The American Society of Civil Engineers (ASCE) Standard 7-05 [1] in Section 1.4 described some details of progressive collapse as follows: "Buildings and other structures shall be designed to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage. This shall be achieved through an arrangement of the structural elements that provides stability to the entire system by transferring loads from any locally damaged region to adjacent regions capable of resisting those loads without collapse". The ASCE standard 7–10 [3] in sections 1.4.1 through 1.4.4 presents minimum strength criteria intended to ensure minimum interconnectivity of structural elements and the existence of a complete lateral force-resisting system with sufficient strength to provide for stability under gravity loads, etc. The U.S. General Services Administration (GSA) [4] and Unified Facilities Criteria (UFC) [5] both discuss analysis and design guidelines for prevention of progressive collapse under extreme loads. The methodology proposed by GSA is based on the Alternate Path Method (APM). The method defines element removal scenarios for which the damaged structure should be analysed to study the system response. The UFC methodology, on the other hand, is a performance-based design approach. It is partly based on the GSA provisions [6]. Several researchers have investigated the progressive collapse of structures. Powell utilized various analysis procedures and found that the increase load factor of 2 proposed for the linear static analysis may display conservative results [7]. Ruth et al. found that a factor of 1.5 better represents the dynamic effect especially for steel moment frames [8]. Kim et al. studied the resistance of steel moment frames using the APM method, recommended in the GSA and UFC guidelines. They observed that a nonlinear dynamic analysis may present larger structural responses [9]. Khandelwal et al. concluded that an eccentrically braced frame is less vulnerable to progressive collapse than a special concentrically braced frame in column removal scenario due to improved system and member layouts in the former compared to the latter [10]. The results of the studies conducted by Fu show that, under the same general conditions, a column removal

* Corresponding author.
E-mail addresses: s_dadras@mail.kntu.ac.ir, dadrassoheil@gmail.com
(S. Dadras Eslamlou).

http://dx.doi.org/10.1016/j.jcsr.2016.04.021
0143-974X/

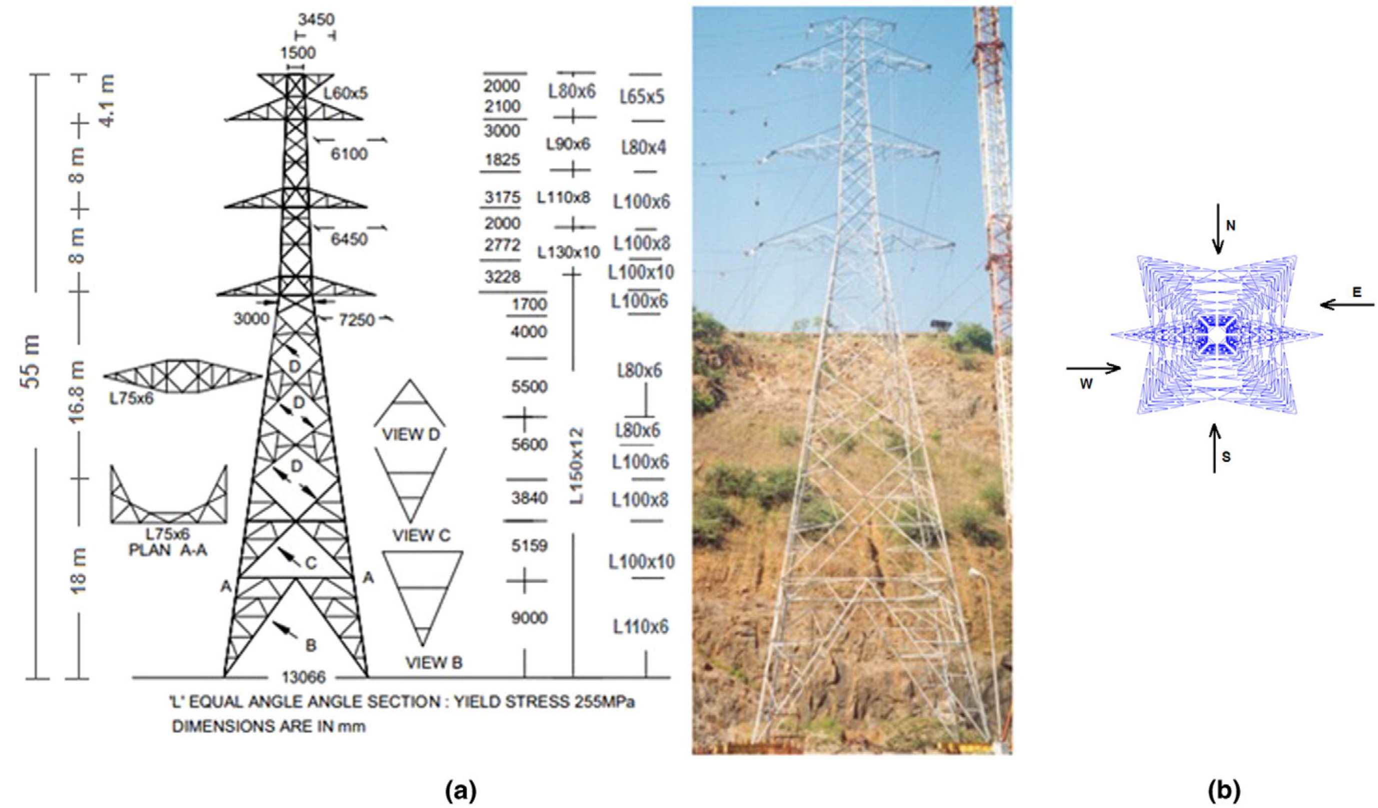

Fig. 1. (a) Geometry of the prototype transmission tower and members' specification; (b) plan of the lattice tower [28].

at an upper story will induce larger vertical displacement than a column removal at ground level [6,11]. Khandelwal and El-Tawil presented the 'pushdown analysis' technique to investigate the robustness of buildings by computing residual capacity and investigating on the collapse modes of the damaged structures. They could also show that the dynamic impact factors after column removal were significantly lower than the commonly used value of 2.0 [12]. Kwon et al. investigated on the progressive collapse resisting capacity of two different tall buildings and concluded that, compared to nonlinear analysis procedures, the linear static method is conservative in predicting progressive collapse resisting capacity of structure based on the scenario of column removal [13]. I. Song et al. simulated the progressive collapse response of a steel frame building by developing two and three-dimensional computer models and comparing them with the experimental data. They concluded that the three-dimensional computer models were more accurate in simulating the response of the structure to column removal [14]. El Kamari et al. studied the deflection of a part of the Roissy Charles de Gaulle Airport and compared the results with the ones measured on site and the ones predicted by the design. They simulated a progressive collapse by reducing the rigidity of the elements which yielded and explained the different incidents of the collapse. They also concluded that construction defects and an improper design caused the collapse [15].

In traditional methods, the analysis of a tower is simplified by performing independent linear analysis on statically determinate subsystems of the structure. First-order linear elastic analysis ignores the effects of material and geometric nonlinearities. In this case, all solid members are treated as linearly elastic. Al-Mashary and Chen have studied a simplified method for static second-order elastic analysis of two-dimensional frames using the matrix form of stability functions for beam-column elements [16]. Albermani and Kitipornchai have applied advanced nonlinear analysis to transmission towers. The spatial configuration of the structure, as well as presence of eccentrically connected asymmetric angle shapes significantly adds to the complexity of analyses. These elements are subjected to axial force and biaxial moments. This makes it impractical to model these structures using conventional three-dimensional methods used for typical truss structures [17]. The same authors later suggested that steel lattice towers should be modelled with beam-column elements using "lumped plasticity, coupled with the concept of the yield surface in force space" [18]. Robert et al. compared the nonlinear analysis results of a truss elements model with frame elements model. In both models, the secondary brace members were taken into consideration. Both modelling techniques yielded similar results, but the model with frame elements was preferable because it allows checking whether flexural effects may lead to premature

Table 1
Loading summary acting on each cross-arm tip.

Case no.	Case title	Conductors loads (kN)			Shield wires loads (kN)		
		Vert. load	Trans. load	Long. load	Vert. load	Trans. load	Long. load
1	Heavy ice	35.53	0	0	10.79	0	0
2	High wind	10.58	15.02	0	1.84	3.13	0
3	Wind & ice	36.75	21.28	0	10.05	8.15	0
4	Unbalanced load	18.76	3.55	12.19	4.60	2.19	4.29
5	Broken wire in case 3	28.01	16.02	53.70	5.03	4.08	37.81

Note: Weight of conductors is included in Vert. Load.

Table 2
Verification of the analytical model using reference [28].

Members' failure force (kN)			Failed members
NE-NASTRAN [28]	SAP2000	OpenSees	
520	517	522	Leg in the first panel
505	495	502.7	Leg in the second panel
35	35	34.7	Bracing in the first panel