14th International Conference on Structural Safety and Reliability - ICOSSAR'25
1-6 June, 2025 - Los Angeles California, USA
R. Ghanem, E. Johnson, S. Masri and A. Olivier (Eds)

SEISMIC VULNERABILITY OF ROOFTOP TELECOMMUNICATION TOWERS AT URBAN SCALE

ALESSANDRO CARDONI[1], JEAN-PIERS CHAVEZ[2] AND GIAN PAOLO CIMELLARO[3]

[1]Department of Structural, Geotechnical, and Building Engineering, Politecnico di Torino
Corso Duca degli Abruzzi 24, 10129 Turin, Italy
alessandro.cardoni@polito.it

[2]Civil and Environmental Engineering Department, Universitat Politècnica de Catalunya
Campus Nord UPC, 08034 Barcelona, Spain
jean.piers.nicolas.chavez@upc.edu

[3]Department of Structural, Geotechnical, and Building Engineering, Politecnico di Torino
Corso Duca degli Abruzzi 24, 10129 Turin, Italy
gianpaolo.cimellaro@polito.it

Key words: Mobile telecommunication network, rooftop towers, seismic vulnerability, damage assessment, infrastructure interdependencies.

Abstract. *Mobile telecommunication networks are essential to support communication services, emergency response, and economic activity. As these systems at the urban level expand, their vulnerability to earthquakes and extreme hazards becomes increasingly critical. There is limited research on urban-scale models, particularly for rooftop-mounted towers, which are more susceptible to seismic damage due to amplification phenomena and building collapses. This paper focuses on common rooftop tower designs, clustering them height and section types, and evaluates their seismic vulnerability using simplified models. The network used as case study is a virtual testbed inspired by an Italian city, where crowdsourced data was used to inform the topology and the features of the components. Time history analyses were performed considering the acceleration recorded on top of the building. Direct physical damage to the towers and electronic component damage are assessed in terms of displacements and drift ratios. This approach provides a scalable method for assessing the seismic risk of telecommunication infrastructures at the urban level. Information about the failed components can be used to update the topology of the network and assess the loss of performance over time to calculate resilience.*

1 INTRODUCTION

Telecommunication networks play a key role in keeping urban communities connected, supporting not only personal communication but also critical services such as media, emergency response, and economic activities. The ongoing expansion of these infrastructures to meet an increasing service demand, demands the evaluation of their vulnerability and resilience to earthquakes and extreme natural hazards, which are often responsible for severe damages. This has a significant impact not only on repair costs and recovery time but also cascading effects on the restoration of other infrastructures and business services dependent on IT services.

Despite notable advancements in the design and seismic performance of these systems, driven largely by insights from past seismic events, their vulnerability remains a pressing concern. Most existing studies focus on isolated structural evaluations of tall, ground-based towers under seismic and wind loads, leaving a gap in understanding the large-scale behavior of urban networks. Telecommunication infrastructures are deeply embedded within urban systems, exhibiting strong interdependencies with power supply, data processing facilities, and transportation access [1, 2]. Failures in one sector can therefore cascade, amplifying the consequences of seismic events. Rooftop-mounted base stations, which are common in dense cities due to space constraints and coverage needs, are particularly vulnerable because their performance is coupled to the seismic response of the supporting buildings [3]. Their anchorage systems, slender geometries, and elevated placement often lead to amplified displacements and increased risk of structural and component damage during ground shaking.

Post-earthquake investigations, such as those following the 2011 Great East Japan earthquake [4], have emphasized the need for resilient communication strategies, including mobile recovery units and decentralized mesh networks. Yet, failure rates remain high relative to other infrastructures, often due to design deficiencies [5]. Moreover, there is a lack of validated physical-based models capable of simulating the dynamic behavior of telecommunication networks. Most approaches rely on qualitative or empirical metrics, limiting their utility for forward-looking risk mitigation and resilience planning [6].

Addressing this gap, this paper introduces a physics-based methodology for assessing the seismic vulnerability of urban telecommunication systems. The case study is a virtual environment inspired by the city of Turin, Italy. The model incorporates network topology, tower characteristics, and building interactions to evaluate both structural damage and communication performance under seismic loading. The study focuses on the damage assessment of rooftop-mounted towers and their electronic components through time-history analyses. Information about tower damage can be combined with the building damage to obtain an updated network topology for further performance and resilience evaluations.

2 METHODOLOGY

Although FEMA [7] provides fragility curves for telecommunication facilities, there is a lack of research focused on the seismic vulnerability of telecommunication towers themselves, particularly at the urban scale those mounted on building rooftops. Given the private ownership and operation of these networks, it is difficult to obtain the actual data for confidentiality reasons, which poses a challenge to detailed seismic analyses. Besides the direct physical damage in the towers, it is also crucial to evaluate damage in the electronic components mounted on them such as cables, antennas, etc. Indeed, even when towers are structurally capable of withstanding significant seismic excitations, their functionality can still be compromised under large displacements.

The damage assessment procedure implemented in this study consists of the following steps:

1. Define a seismic scenario.

2. Through a ground motion model, determine the two horizontal seismic inputs along the principal axes for each building.
3. Perform nonlinear time history analyses and calculate the maximum inter-storey drift.
4. Link the inter-storey drift to a structural damage state following the HAZUS categories.
5. Use the acceleration time histories computed at the top of each building along the two horizontal principal directions as input at the base of each tower.
6. Perform time history analyses to compute the response of the towers.
7. Evaluate possible physical damage in the towers.
8. Based on the maximum displacements at the top of the towers, calculate the drift ratios.

According to the Structural Standard for Antenna Supporting Structures and Antennas and Small Wind Turbine Support Structures (TIA-222-H) [8], a 3% drift ratio can make the electronic components fail.

This work extends the methodology proposed by Cardoni et al. [9] who related the vulnerability of urban telecommunication network to the vulnerability of the built environment. In their work they assumed that towers would not get damaged directly by the earthquake. Instead, they considered that only towers mounted on top of buildings subject to partial and complete collapses would fail. Considering explicitly the vulnerability of the towers through time-history analyses allows to refine the analysis. Once the damage to the towers and electronic components is combined with the indirect damage due to partial and complete collapses of buildings, it is possible to update the network topology considering only the functional antennas. The performance can be evaluated in terms of throughput. This is calculated via a procedure that maps the signal-to-interference-plus-noise ratio (SINR) to the throughput.

3 CASE STUDY

The case study is a virtual testbed called Ideal City, which covers an area of 120 km^2 and has about 900,000 inhabitants. It is representative of a typical medium size European city, and it is inspired by the city of Turin, Italy. Its building portfolio consists of 23,420 residential buildings, categorized into reinforced concrete (63%) and masonry (37%). The seismic response and damage assessment are performed through the surrogate model proposed by Marasco et al. [10], where each building is reduced to a single degree of freedom system described by a backbone curve.

Various infrastructures serve the city, including a mobile telecommunication network that is managed by three main mobile network operators (MNOs). The main elements at the urban level are: (1) base station controllers (BSCs); (2) base transceiver stations (BTSs), i.e. steel towers supporting antennas. These can either be tall, raw-land towers or rooftop mounted. Since the infrastructure is privately owned, most of the details to model the network were collected through CellMapper, a crowd-sourced database for cellular tower [11].

Figure 1 illustrates the proposed network topology for one of the MNOs serving approximately 1/3 of the population. The different line weights symbolize the importance of the connections. The thinner one is the link between BSCs and BTSs, the medium one is the link between aggregation BSCs and edge BSCs, the thickest is the link between core BSCs and aggregation BSCs. The proposed topology was generated using a hybrid approach, combining the star topology for the outer elements of the system and a hierarchical three-layer structure. More details can be found in [9]. The total number of BTSs is 359, including 53 raw-land towers and 233 rooftop-mounted towers. Out of these, 157 are monopoles and 76 are lattice structures.

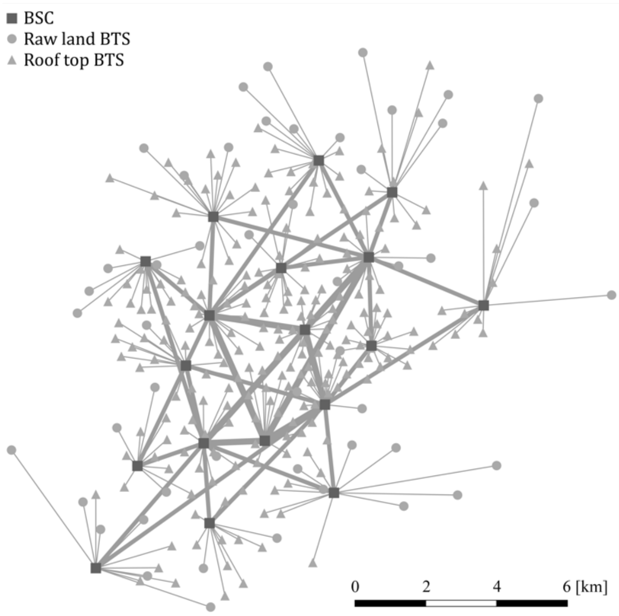


Figure 1: Network topology for the selected MNO.

4 ROOFTOP TOWER MODELS

All the models and analyses have been implemented in OpenSeesPy.

4.1 Monopole model

Each monopole tower is idealized as a cantilevered steel circular hollow section. The total height varies from 2 m to 6 m. The monopole is modeled as a force-based beam-column element. Although a single element could capture the global response quickly, at least two elements are recommended for higher-mode fidelity and curvature accuracy when local buckling or yielding is critical. Therefore, the node layout produces two nodes for the default discretization: node 0 at the base and node 1 at the top. At the base, it is assumed that the monopole is connected to the roof structure through a steel base plate with anchor bolts. Therefore, in the model the base node is fixed in all six degrees of freedom, simulating a rigid foundation. On the other hand, the node at the top remains free to move, carrying both vertical and horizontal loads. The top node is where the dynamic response in terms of displacements and accelerations is evaluated.

The “forceBeamColumn” element employs distributed plasticity, meaning that internal forces are integrated along the element length, and cross-section behavior is represented by a fiber discretization. The fiber mesh consists of 80 circumferential fibers in one radial layer to deliver a fine capture of stress gradients while keeping the computational cost negligible for single-element models.

The response is evaluated through the Lobatto integration with five Gauss points, arguably the most accurate option for uniform sections, considering six degrees of freedom, i.e., three translations and three rotations. Monopoles have been clustered in groups based on their total height. Clusters were defined each 0.5 m and each of them has been assigned a fiber section representing a steel circular hollow section with outer diameter D_{ext} and wall thickness t (Table 1). These section properties are based on common commercial catalogues as it was not possible to obtain the actual dimensions for the entire network. Figure 1 exemplifies one of the 3D monopole models.

Table 1: Monopole tower sections

Tower cluster	Height [m]	Outer diameter D_{ext} [mm]	Wall thickness t [mm]	No. of elements (discretization)
1	2.0	80	3	2
2	2.5	80	3	2
3	3.0	80	3	3
4	3.5	90	3	3
5	4.0	90	3	4
6	4.5	90	3	4
7	5.0	114	3	5
8	5.5	114	3	5
9	6.0	114	3	6

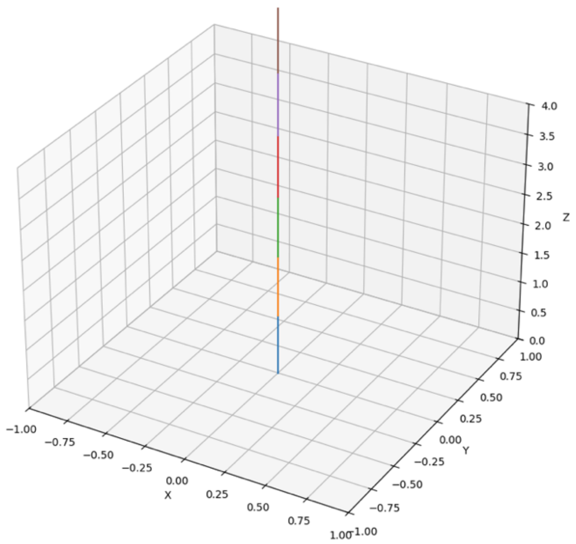


Figure 2: 3D representation of the monopole model for cluster 9 (height = 6 m).

The material of this type of structures is typically steel S235 according to Eurocodes and it has been modeled through “Steel02”, which implements the Giuffré–Menegotto–Pinto model, capable of reproducing (i) Elastic–plastic transition with isotropic hardening, (ii) Bauschinger effect under load reversals, (iii) Kinematic hardening controlled by the parameter b (here assumed equal to 0.01). The elastic modulus is E = 200 GPa and the yield stress is Fy = 350 MPa. The self-weight of the circular hollow section is computed analytically and lumped at the nodes. A vertical load of 1.5 kN has been applied at the top of the monopole to simulate the weight of three antennas oriented at 120°. The following steps summarize the analysis workflow implemented in OpenSeesPy.

1. Model generation functions: assemble nodes, elements, section, material, and mass for each tower in isolation.
2. Driver run_analysis_tower() applies a constant gravity load (-1.5 kN) and assigns two orthogonal base motions using UniformExcitation linked to a Path time-series derived from the acceleration time histories in both x and y directions. Newmark implicit integration (γ = 0.5, β = 0.25) advances the solution.
3. Rayleigh damping is set equal to 5 % for the fundamental mode.
4. Recorders capture the displacement and acceleration at the top and base reactions

The model allows capturing:

1. Flexural yielding and distributed plastic hinges along the shaft (via fiber section).
2. Torsional stiffness through GJ, although torsional plasticity is not modeled (OpenSees does not currently support torsional yielding in the “Steel02” model).
3. Axial-flexural interaction under gravity combined with seismic bending.

Second-order P–Δ effects are neglected globally because a linear geometric transformation is used.

4.2 Lattice tower model

The lattice towers of the network were clustered in groups based on their total height. Given that heights range between 2.5 m and 7.5 m, eleven clusters were defined at 0.5 m steps. Since it was not possible to obtain the actual sections for the entire network, it was assumed that each tower is composed of four vertical legs and single horizontal and diagonal braces on every face. A square base of 0.5 m × 0.5 m is presumed. A simplified geometry was adopted, considering a reduced number of section modules. Each module consists of four corner nodes at each floor. Floor-to-floor spacing is uniform, meaning that $h_{module} = Height/no.of\ modules$. At the base, it is assumed that the lattice tower is welded to a steel base plate and connected to the roof structure either directly with anchor bolts or via steel base frames or concrete foundation. Therefore, the base node is fully fixed in all six degrees of freedom, simulating a rigid foundation. The top node is where the dynamic response in terms of displacements and accelerations is evaluated.

All structural members (vertical legs and horizontal and diagonal braces) are modeled with distributed-plasticity force-based beam-column elements through a fiber discretization. As in the previous case, the fiber mesh consists of 80 circumferential fibers in one radial layer. The response is evaluated according to Euler–Bernoulli kinematics, since the shear-rigid assumption is suitable for slender tubes, and Lobatto integration with five Gauss points.

Table 2 summarizes the geometric parameters and steel tube sizes used for columns and diagonals. Figure 2 illustrates one example of the 3D lattice tower model.

Table 2: Lattice tower sections

Tower cluster	Height [m]	Vertical legs Ø×t [mm]	Horizontal and diagonal braces Ø×t [mm]
1	2.5	50x2.5	20x2.0
2	3.0	50x2.5	20x2.0
3	3.5	50x2.5	20x2.0
4	4.0	50x2.5	20x2.0
5	4.5	75x5.0	25x2.0
6	5.0	75x5.0	25x2.0
7	5.5	75x5.0	25x2.0
8	6.0	75x5.0	25x2.0
9	6.5	110x6.0	30x2.0
10	7.0	110x6.0	30x2.0
11	7.5	110x6.0	30x2.0

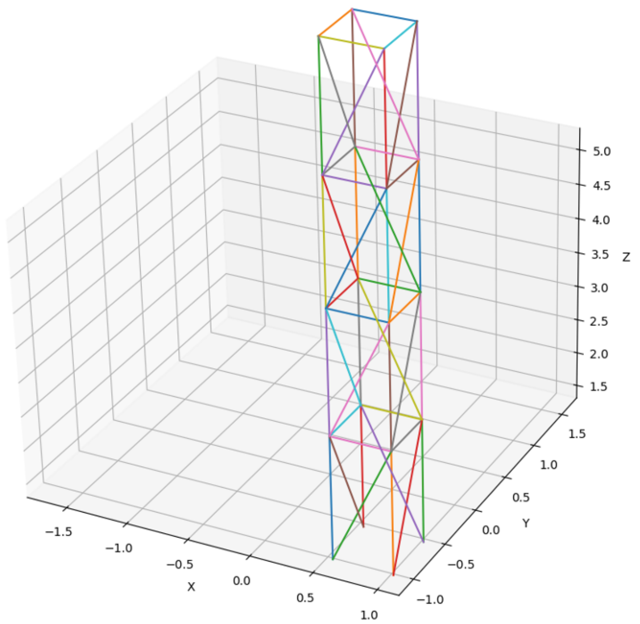


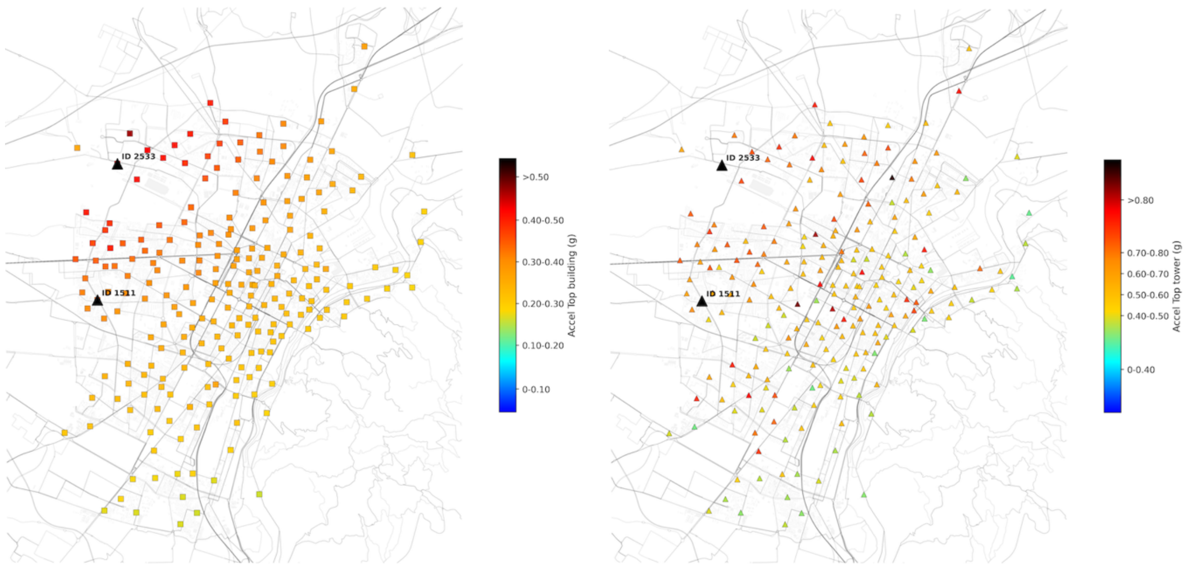
Figure 3: 3D representation of the lattice tower model for cluster 11 (height = 7.5 m).

All the elements share the same steel material properties, represented by the "Steel02" model. The elastic modulus is $E = 200$ GPa and the yield stress is $Fy = 350$ MPa. The self-weight is computed automatically from steel density and area for each member type. The mass of each section module is lumped at each floor level and distributed equally to the four corner nodes. A vertical load of 1.5 kN has been applied at the top to simulate the weight of three antennas oriented at 120°. This is also distributed equally to the four corner nodes. It is worth mentioning that for the slender nature of the lattice structure, rotational inertia can be neglected. The following steps summarize the analysis workflow implemented in OpenSeesPy.

1. Rayleigh damping is set equal to 5 % for the fundamental mode.
2. Newmark implicit integration ($\gamma = 0.5$, $\beta = 0.25$) advances the solution.
3. Solver: Newton–Raphson iterations with "BandGen" solver and Transformation constraint handler.
4. Recorders export the time histories of top-node displacement, top-node acceleration and base shear reaction for every analysis.

5 TIME-HISTORY ANALYSES

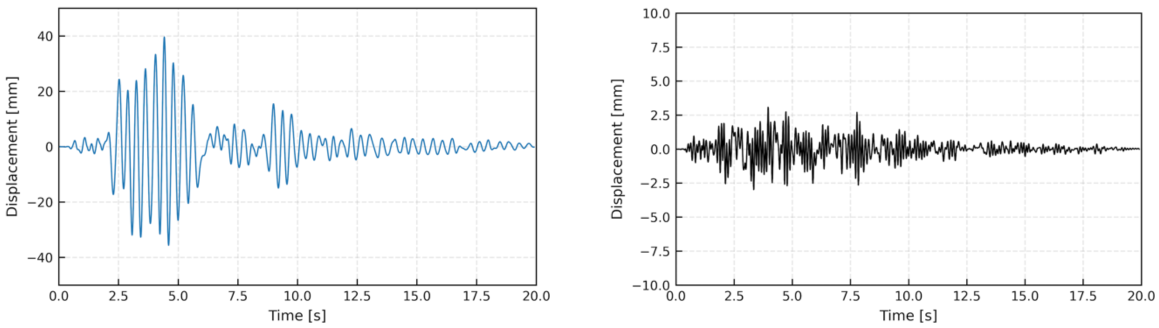
The 1994 Northridge earthquake scenario was simulated and applied to the Ideal City virtual testbed. The epicenter was located just outside the city in an imaginary fault running in the North-West boundary. The distance to the downtown is about 9 km. Using the Campbell & Bozorgnia ground motion model [13], the scaled acceleration time histories were obtained at each building location. Then, through the surrogate building model proposed by [10], the acceleration at the top of the buildings were calculated (Figure 4a).



(a) (b)

Figure 4: Map of the peak acceleration (a) at the top of the buildings and (b) at the top of the towers.

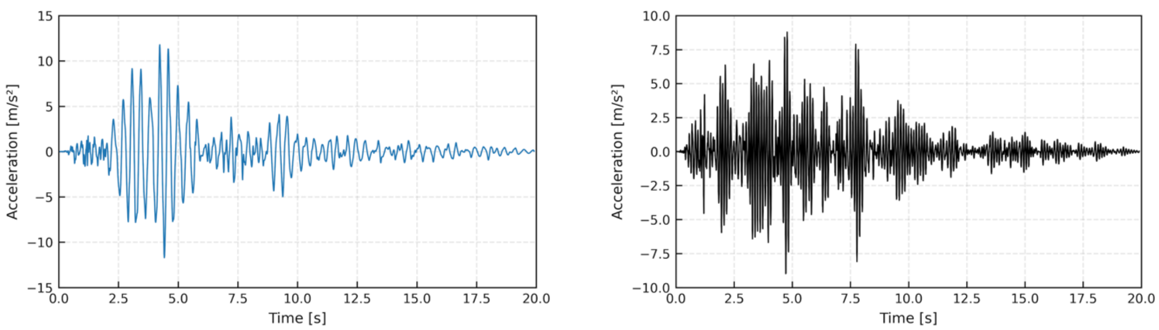
These were used as the input of the time-history analyses of each rooftop telecommunication tower. The outputs of each analysis were the shear force at the base of the towers and the acceleration and displacement time histories at the top of the towers (Figure 4b). The seismic analysis showed that both monopoles and lattice towers had a mostly linear response, with no physical damage found on the structures. The most significant displacement time histories are reported in Figure 5. Overall, monopoles (Figure 5a) showed larges top displacements compared to lattice towers (Figure 5b). However, small values of drift ratios were observed. For monopoles the maximum drift was about 0.7%, with an average of 0.2%. For lattice structures, the maximum drift was about 0.1%, with an average of 0.04%. These values are abundantly lower than the 3% maximum drift threshold suggested by the Structural Standard for Antenna Supporting Structures and Antennas and Small Wind Turbine Support Structures [8]. Therefore, it is assumed that the electronic components suffer no direct damage caused by the ground motion, confirming the original assumption done by Cardoni et al. [9], where they considered only the indirect damage caused by building collapses.



(a) (b)

Figure 5: Displacement time histories of (a) monopole (height = 6 m) and (b) lattice tower (height = 7 m).

Nonetheless, looking at the acceleration time histories, large amplifications at the top of the towers were observed. Figure 6 illustrates the acceleration records at the base of the building, at the base of the tower, and at the top of the most excited monopole (Figure 6a,b,c) and lattice structure (Figure 6d,e,f). As it can be seen, the amplification in the case of the monopole is about 3.5 times, while for the lattice is almost 2 times. This aspect should be further investigated as in the literature there are no clear indications on the effect of acceleration on electronic components mounted on telecommunication towers.



(a) (d)

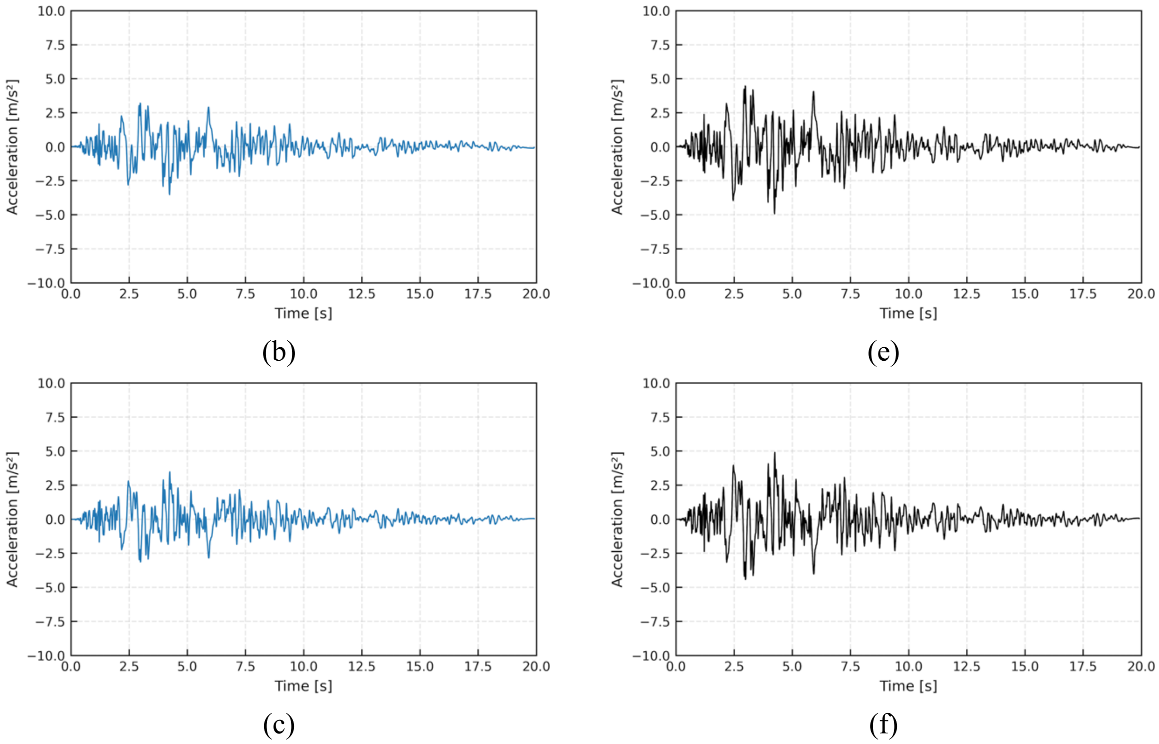


Figure 6: Acceleration time histories for a monopole (height = 6 m) (a) at the top, (b) at the base, (c) at the base of the building, and for a lattice tower (height = 7 m) (d) at the top, (e) at the base, (f) at the base of the building.

6 CONCLUSIONS

This study proposed a physics-based approach for evaluating the seismic vulnerability of urban telecommunication networks, with a focus on rooftop-mounted towers embedded within the built environment. By incorporating structural models of different tower typologies into a virtual testbed inspired by the city of Turin, the methodology allowed for a proper simulation of network performance under earthquake loading. Since it was not possible to obtain the actual dimensions of the rooftop towers for the entire network, common commercial catalogues were used to determine section types. A more refined approach would be designing each structure according to the actual vertical, wind, and seismic loading conditions. This approach would require a significant computational effort. Moreover, rooftop towers with modest size are often designed through simplified procedures and tend to be overdesigned to match the standard section types available in manufacturers' catalogues.

Time history analyses revealed that both monopoles and lattice towers exhibit primarily linear behavior, with negligible structural damage observed. Drift ratios remained significantly below the limit defined by current standards, confirming the adequacy of these systems even under strong seismic demands. These findings support prior assumptions in the literature that electronic damage is unlikely to arise directly from ground shaking, provided that the host buildings remain structurally intact.

Nevertheless, the analysis highlighted a potentially critical concern related to the significant acceleration amplifications observed at the top of the towers. Given the absence of clear design guidelines regarding the sensitivity of electronic components to such amplified accelerations, this aspect warrants deeper investigation. Future work should focus on characterizing the dynamic fragility of telecommunications hardware and incorporating component-level damage models to more accurately quantify network resilience.

REFERENCES

[1] Ouyang, M. Review on modeling and simulation of interdependent critical infrastructure systems. *Reliability Engineering & System Safety, 121*, (2014):43–60.
[2] Modica, C., Lami, I. M., & Marzullo, F. M. Interdependencies among critical infrastructures in urban areas: A resilience-based approach. *International Journal of Disaster Risk Reduction, 94*, (2023):103797.
[3] Cruz, A. M., & Miranda, E. Post-earthquake damage to industrial facilities and its impact on production. *Earthquake Spectra, 32*(2), (2016):1161–1181.
[4] Nemoto, T., & Hamaguchi, T. Enhancing resilience in wireless communication networks: Lessons from the Great East Japan Earthquake. *Telecommunication Systems, 56*(2), (2014):207–217.
[5] Gomes, C., Antunes, A. P., & Ribeiro, C. Improving resilience of communication systems against natural disasters. *Reliability Engineering & System Safety, 152*, (2016):149–162.
[6] Patra, A., Dong, Y., & Gardoni, P. Seismic risk assessment of interdependent infrastructure systems: A review of modeling approaches. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, 6*(2), (2020): 04020001.
[7] FEMA, "Multi-hazard loss estimation methodology, earthquake model" Washington, DC, USA: Federal Emergency Management Agency (2003).
[8] TIA-222-H Structural Standard for Antenna Supporting Structures and Antennas and Small Wind Turbine Support Structures (2017).
[9] Cardoni, Alessandro, Simone Lucco Borlera, Francesco Malandrino, and Gian Paolo Cimellaro. Seismic vulnerability and resilience assessment of urban telecommunication networks. *Sustainable Cities and Society* 77 (2022): 103540.
[10] Marasco, Sebastiano, Ali Zamani Noori, Marco Domaneschi, and Gian Paolo Cimellaro. "A Computational Framework for Large-Scale Seismic Simulations of Residential Building Stock." *Engineering Structures* 244 (2021):112690. https://doi.org/10.1016/j.engstruct.2021.112690.
[11] CellMapper. Cellular Coverage and Tower Map. Available at www.cellmapper.net.
[12] McKenna, Frank, Gregory Louis Fenves, and Michael Scott. "OpenSees (Open System for Earthquake Engineering Simulation)." University of California, Berkeley, CA: Pacific Earthquake Engineering Research Center (2000).
[13] K.W. Campbell, Y. Bozorgnia, NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s, Earthq. Spectra 24 (2008):139–171.