Proceedings of International Structural Engineering and Construction, 10(1), 2023
State-of-the-art Materials and Techniques in Structural Engineering and Construction
Edited by Karatas A., Iranmanesh A., Gurgun A., Yazdani, S., and Singh, A.

ISSN: 2644-108X
www.doi.org/10.14455/ISEC.2023.10(1). STR-32

EVALUATING STRUCTURAL RESILIENCY OF PUBLIC SCHOOLS AS EMERGENCY SHELTERS IN NATURAL DISASTERS

AMANDA BAO[1], ZICO ARACHIE[1] and ADRIANA RODRIGUEZ[1]

[1]*Dept of Civil Engineering Technology. Environmental Management and Safety, Rochester Institute of Technology, Rochester, New York, United States*

Public schools are the second largest sector of public infrastructure spending following highways, and there are about 84,000 public schools with 100,000 buildings in the United States. In addition to their primary functions as learning facilities, public schools usually serve an important role as emergency shelters and community resilience hubs during and after natural disasters, such as earthquake, windstorm, and flooding. In order to effectively fulfill the secondary function as emergency shelters, the school infrastructures need to be operational during and after the disasters. However, there are gaps between the existing school building structural capacities and the requirements of essential buildings as emergency shelters. In this paper, a generic 3-story steel framing K-12 school building will be analyzed based on the design loads and load combinations specified in ASCE-7: Minimum Design Loads for Buildings and Other Structures. The design loads in ASCE-7 are continuously updated to address the climate changes and new challenges, which will be reflected in the analysis to compare the building design criteria and structural capacities from the past two decades. The structural capacity will be evaluated as an emergency shelter/public assembly (Risk Category IV) during and post disasters, versus a regular school building (Risk Category II or III). Full live loads will be combined with the natural disaster loads to evaluate the school building capacity as a community resiliency hub. The results will be used to assess the structural resilience level of school buildings functioning as emergency shelters in natural disasters.

Keywords: Community resilience hub, Essential building, Emergency shelter, Structural loads

1 INTRODUCTION

Public schools are the second largest sector of public infrastructure spending following highways, and there are about 84,000 public schools with 100,000 buildings in the United States (ASCE 2021). In the wake of natural disasters, despite the awareness and intention to increase physical resilience of schools, the opportunity of leveraging investment in the school reconstruction may be lost in case of inadequate knowledge and preparation for schools' capacity and recovery (GADRRRES, 2015). The tragic destruction due to recent natural disasters is solid evidence of the vulnerability of schools' physical resilience. For example, Hurricane Katrina in the United States caused 700 schools' closure due to significant damages in 2005.

Resilience to natural disasters is of great importance for school buildings and infrastructure to ensure not only the safety of children and the quality of education, but also the economic and social growth for the broader community resilience. Advance preparation and sufficient knowledge of the structural capacity and rapid recovery of school buildings and infrastructure during and post natural disasters may enhance the community resilience.

In addition to their primary functions as learning facilities, public schools usually serve an important role as emergency shelters and community resilience hubs during and after natural disasters, such as earthquake, flood and windstorm. In order to effectively fulfill the secondary function as emergency shelters, the school infrastructures need to be operational during and after the disasters. However, there is a gap between the existing school building structural design and the requirements of essential buildings as emergency shelters. In this study, a generic school building is evaluated as an emergency shelter/public assembly (Risk Category IV, ASCE-7, 2022) during and after the natural disasters, versus a regular school building (Risk Category II, ASCE-7, 2022). The live loads representing heavy public occupancy are combined with the natural disaster loads in the analyses to evaluate the school building capacity as a community resiliency hub. The results will be used to assess the structural resilience level of school buildings functioning as emergency shelters in natural disasters.

Design recommendations and mitigation strategies for school building resilience to natural disasters will be proposed according to the assessment results. The trends of climate change impact on school building design will be analyzed and projected according to the ASCE-7 codes.

2 METHODOLOGY

In this study, a generic 3-story steel framed K-12 school building, as shown in Figure 1, will be analyzed based on the design loads and load combinations specified in ASCE 7: Minimum Design Loads for Buildings and Other Structures. Since natural disasters heavily rely on geographical locations, this study will focus on two predominant disasters: earthquake and windstorm, respectively.

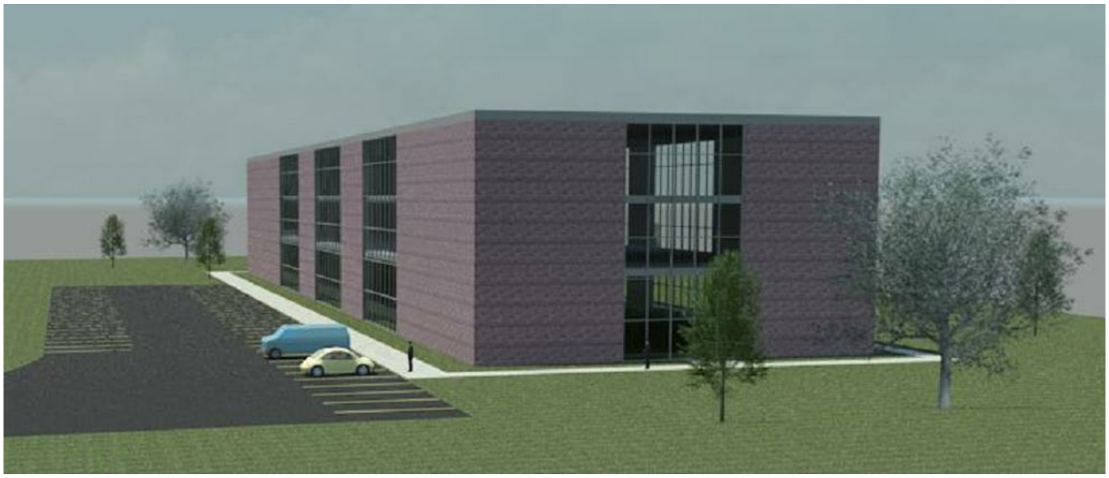

Figure 1. A Generic 3-Story Steel Frame School Building

In the structural capacity analysis, the natural disaster loads include seismic loads and wind loads as specified in ASCE-7, and a higher magnitude of live loads representing public assembly will be considered for the natural disaster community emergency shelters function in addition to the learning facility.

The building's plan dimensions are 81.08 meters (266 feet) by 28.65 meters (94 feet), with the column spacing of 11.58 meters (38 feet) along the long dimension and 10.67-7.32-10.67 meters (35-24-35 feet) along the short dimension as shown in Figure 2. Typical story heights are 4.27 meters (14 feet), except for the first story, which has a height of 5.49 meters (18 feet) to allow for laboratories. The building lateral force resisting system uses the braced frame. The building's elevation views and the framing plan are also shown in Figure 2.

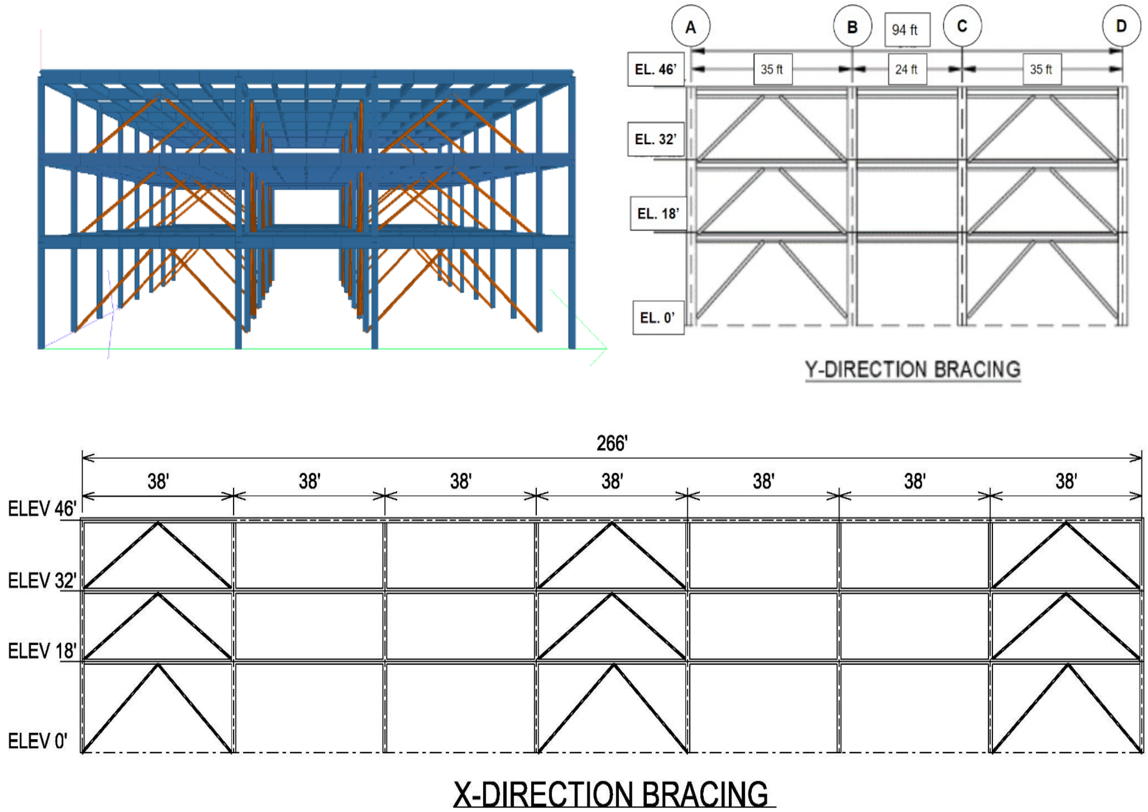

Figure 2. Building Elevations and Framing Plan

The building's 3-D structural model is set up using the structural analysis software STAAD.Pro. The governing design loads in a typical interior floor beam, interior floor girder, interior ground level column, and a diagonal bracing member are determined and compared according to the ASCE-7 2002 and ASCE-7 2022 Hazard Tool, respectively. The school building is evaluated as an essential building used as an emergency shelter or public assembly with the Risk Category IV during and after the natural disasters, versus a regular school building designed as the Risk Category II. In the analysis, the live load value is selected according to the public assembly occupancy, and the full live load are combined with the natural disaster loads in the analyses to evaluate the school building capacity as a community resiliency hub. The risks of natural disasters are site specific and depend on geographical locations. In this study, two geographical locations are selected for the analysis and comparison according to FEMA's National Risk Index Map, as listed in Table 1.

Table 1. Building Locations and Natural Disaster Risk Index

Location	**Hurricane**	**Earthquake**	**Flooding**
Bronx County, NY	Relatively high	Relatively high	Very high
Miami-Dade County, FL	Very high	Relatively low	Very high

3 RESULTS

The structural loads are determined according to the ASCE 7 codes. In the analysis, the loads according to the ASCE 7-2002 and the ASCE 7-2022 are compared to show the impact of the building age as well as the climate change on the structural design. The design loads for a regular classroom building with the Risk Category II are compared with the loads for an emergency shelter with the Risk Category IV to show the differences due to the building's emergency shelter function during the natural disasters. The summary of the structural loads is listed in Table 2 and Table 3.

Table 2. Load summary for the building located in Bronx County, NY, USA

Load Type	**ASCE 7-2002 Classroom**	**ASCE 7-2002 Emergency Shelter**	**ASCE 7-2022 Classroom**	**ASCE 7-2022 Emergency Shelter**
Roof dead load	1.436 kPa (30 psf)	1.436 kPa (30 psf)	1.436 kPa (30 psf)	1.436 kPa (30 psf)
Roof live load	0.958 kPa (20 psf)	0.958 kPa (20 psf)	0.958 kPa (20 psf)	0.958 kPa (20 psf)
Floor dead load	3.830 kPa (80 psf)	3.830 kPa (80 psf)	3.830 kPa (80 psf)	3.830 kPa (80 psf)
Floor live load	2.633 kPa (55 psf)	4.788 kPa (100 psf)	2.633 kPa (55 psf)	4.788 kPa (100 psf)
Snow load	1.436 kPa (30 psf)	1.734 kPa (36 psf)	2.298 kPa (48 psf)	3.160 kPa (66 psf)
Wind speed	187 km/h (116 mph)	241 km/h (133 mph)	187 km/h (116 mph)	209 km/h (130 mph)
Seismic coefficient C_s	0.043	0.065	0.092	0.138

Table 3. Load summary for the building located in Miami-Dade County, FL, USA

Load Type	**ASCE 7-2002 Classroom**	**ASCE 7-2002 Emergency Shelter**	**ASCE 7-2022 Classroom**	**ASCE 7-2022 Emergency Shelter**
Roof dead load	1.436 kPa (30 psf)	1.436 kPa (30 psf)	1.436 kPa (30 psf)	1.436 kPa (30 psf)
Roof live load	0.958 kPa (20 psf)	0.958 kPa (20 psf)	0.958 kPa (20 psf)	0.958 kPa (20 psf)
Floor dead load	3.830 kPa (80 psf)	3.830 kPa (80 psf)	3.830 kPa (80 psf)	3.830 kPa (80 psf)
Floor live load	2.633 kPa (55 psf)	4.788 kPa (100 psf)	2.633 kPa (55 psf)	4.788 kPa (100 psf)
Snow load	0 kPa (0 psf)	0 kPa (0 psf)	0.144 kPa (3 psf)	0.287 kPa (6 psf)
Wind speed	241 km/h (150 mph)	248 km/h (173 mph)	269 km/h (167 mph)	298 km/h (185 mph)
Seismic coefficient C_s	0.0138	0.0208	0.0132	0.0198

The 3-D finite element models are built using STAAD.Pro to analyze the governing design loads in the structural members. The governing design forces are obtained using the ASCE LRFD Load Combinations specified in ASCE 7-2002 and ASCE 7-2022, respectively. Table 4 and Table 5 list the maximum internal forces in the typical structural members for comparison. The results reflect the changes of the governing forces over time, occupancy function and geographical location.

Table 4. Governing structural member forces for the building located in Bronx County, NY, USA

Load Type	**ASCE 7-2002 Classroom**	**ASCE 7-2002 Emergency Shelter**	**ASCE 7-2022 Classroom**	**ASCE 7-2022 Emergency Shelter**
Roof beam	Shear force=49.8 kN Moment=144 kN-m	Shear force=55.2 kN Moment=160 kN-m	Shear force=48.9 kN Moment=141 kN-m	Shear force=72.1 kN Moment=209 kN-m
Floor beam	Shear force=137.9 kN Moment=395 kN-m	Shear force=191.3 kN Moment=548 kN-m	Shear force=137.9 kN Moment=395 kN-m	Shear force=191.3 kN Moment=548 kN-m
Floor girder	Shear force=418 kN Moment=1452 kN-m	Shear force=578 kN Moment=2017 kN-m	Shear force=418 kN Moment=1452 kN-m	Shear force=578 kN Moment=2017 kN-m
Column	Compression=2091 kN	Compression=2820 kN	Compression=2086 kN	Compression=2834 kN
Bracing	Compression=262 kN	Compression=343 kN	Compression=356 kN	Compression=543 kN

Table 5. Governing structural member forces for the building located in Miami-Dade County, FL, USA

Load Type	**ASCE 7-2002 Classroom**	**ASCE 7-2002 Emergency Shelter**	**ASCE 7-2022 Classroom**	**ASCE 7-2022 Emergency Shelter**
Roof beam	Shear force=40 kN Moment=117 kN-m	Shear force=40 kN Moment=117 kN-m	Shear force=41 kN Moment=118 kN-m	Shear force=41.3 kN Moment=119 kN-m
Floor beam	Shear force=137.9 kN Moment=395 kN-m	Shear force=191.3 kN Moment=548 kN-m	Shear force=137.9 kN Moment=395 kN-m	Shear force=191.3 kN Moment=548 kN-m
Floor girder	Shear force=418 kN Moment=1452 kN-m	Shear force=578 kN Moment=2017 kN-m	Shear force=418 kN Moment=1452 kN-m	Shear force=578 kN Moment=2017 kN-m
Column	Compression=2015 kN	Compression=2731 kN	Compression=2020 kN	Compression=2740 kN
Bracing	Compression=369 kN	Compression=489 kN	Compression=307 kN	Compression=387 kN

Comparing Table 4 with Table 5, geographical locations affect the roof framing design more than the floor framing, because the roof is exposed to snow and wind. The governing forces in bracings are very sensitive to geographical locations, because the bracings are mainly designed to resist the lateral loads, such as wind loads and seismic loads. The governing forces for the same member change over time due to the design load update in the ASCE-7.

Using the school building as an emergency shelter during natural disasters will significantly overload the structural members. The function as the community resilience hub requires the school building to be operational during and after the natural disasters. The physical resilience level is critical for the school buildings to serve this role, and the structural members need to be designed to withstand the disaster loads and the heavier live load for shelters.

4 CONCLUSIONS

The following conclusions can be drawn according to the analysis results.

- School buildings are recommended to be designed as essential buildings with the Risk Category IV to fulfill the community resilience hub function safely.
- The load demands of an emergency shelter during the natural disasters can be 30% to 50% higher than the load demands of a regular building in structural design.
- The governing internal forces in the structural members, such as beams, girders, columns and braces are significantly higher in an emergency shelter than the internal forces in a

regular school building. The structural member design difference can be as high as 50% in terms of the member sizes.

- Geographical location plays an important role in determining the natural disaster loads and risk levels.
- The design loads related to the natural disasters continuously change over time due to climate change and better knowledge of data collection and analysis. For the new building design, the latest design codes are recommended to ensure the reliable design load calculations.

Acknowledgements

The authors would like to acknowledge Dr. Jennifer Schneider, Eugene Fram Chair of Rochester Institute of Technology, for her support and contribution to this study.

References

American Society of Civil Engineers, *2021 Report Card for America's Infrastructure*, ASCE, 2021
ASCE 7-2002: *Minimum Design Loads for Buildings and Other Structures*, American Society of Civil Engineers, 2002.
ASCE 7-2022: *Minimum Design Loads for Buildings and Other Structures*, ASCE, 2022.
ASCE 7 Hazard Tool: https://asce7hazardtool.online/
Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook, *3rd Edition,* FEMA P-154, 2015.
FEMA's National Risk Index Map: https://hazards.fema.gov/nri/map
Global Alliance for Disaster Risk Reduction & Resilience in the Education Sector (GADRRRES), *Towards Safer School Construction: A Community-based Approach*, 2015.