

# Engineering Adaptation to Climate-Driven Structural Hazards: A Comparative Review of Fire, Earthquake, and Tornado Resilience

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## ABSTRACT

Climate change has intensified the frequency and severity of natural hazards, requiring structural engineers to develop more resilient strategies against fire, earthquake, and tornado events. This literature review examines how structural engineering is adapting to climate-driven hazards through advances in materials, Artificial Intelligence (AI) modeling, and design. Advances in materials, including shape-memory alloys and high-performance fiber-reinforced concrete, improve durability and post-event recoverability, while performance-based and interdisciplinary design approaches provide more efficient multi-hazard resilience. Despite this progress, widespread implementation is limited by high costs, inconsistent global codes, retrofitting challenges, and resource constraints in developing countries. This review underscores the need for global collaboration, unified frameworks, and expanded investment to ensure equitable access to hazard-resistant technologies. Overall, the findings show that structural engineering is rapidly evolving toward more sustainable, data-driven, and adaptable solutions capable of addressing climate-driven risk.

**Keywords:** natural hazards; fire; earthquake; tornado; climate change; AI-based modeling; performance-based designs; frameworks; sustainability

## INTRODUCTION

Natural hazards pose a significant threat to humanity, endangering both lives and infrastructure. Earthquakes and tornadoes remain largely uncontrollable, while fires—once considered containable—are increasingly difficult to stop. As a result, communities depend on resilient infrastructure to withstand these hazards. Climate change has further intensified the impact and frequency of natural disasters such as wildfires and tornadoes (Figure 1). Recent reports show that both

the frequency and severity of fire and tornado hazards have risen over the past 20 years compared to previous decades (1).

Fires are among the most common natural disasters, originating not only from climate change but also from human activities such as unattended cooking. Fire propagation depends on heat transfer, building materials, construction type, and fire intensity. Earthquakes are extremely destructive, causing ground shaking and foundation failure that can lead to building collapse. Tornadoes present severe risks as well, creating intense localized wind pressures and debris impacts due to their rotating vortex-driven wind fields (2, 3).

Throughout this narrative review, we will be exploring how each of these natural disaster functions differently; the level of damage depends largely on the building materials, structural system, and overall design. Early detection and warning systems also play a critical role

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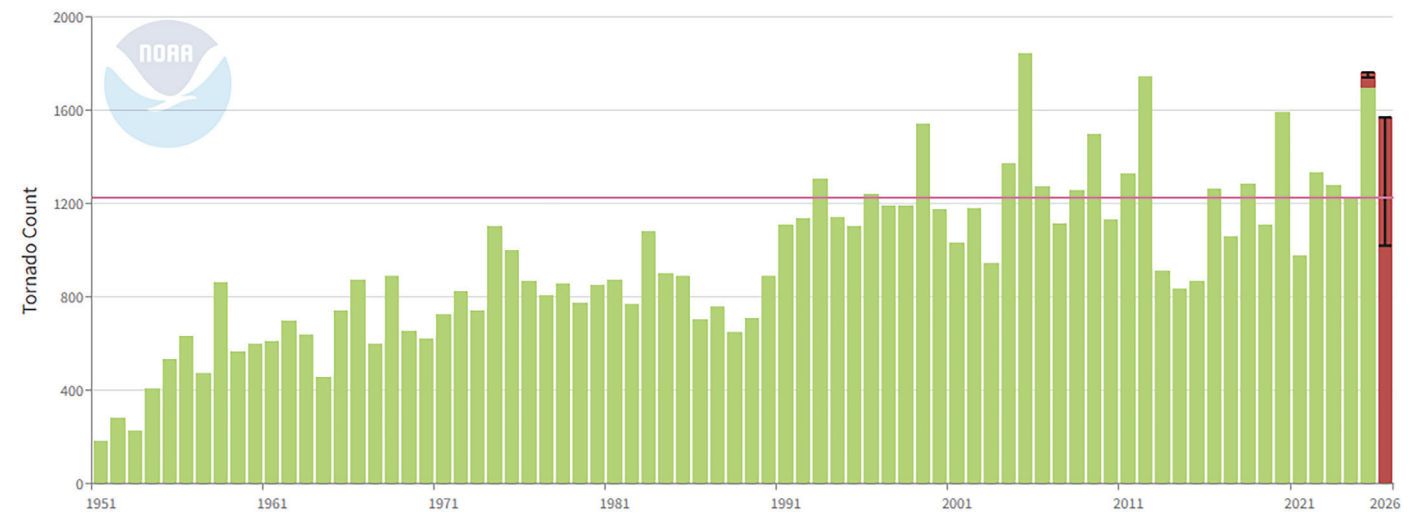
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## U.S. Tornadoes

March-February



Source: Storm Prediction Center (SPC)

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**Figure 1.** Annual frequency of tornadoes in the United States (1951–2026). Time-series data illustrate long-term trends in tornado occurrence, reflecting increasing variability and intensity associated with climate-driven hazard patterns. The dataset is derived from the National Oceanic and Atmospheric Administration (NOAA) Storm Prediction Center [8].

in innovation to each of these disasters, as many lives can be saved with information about incoming disasters. However, each one requires a different focus. When looking at fire protection, passive and active systems are often required to stop the fire quickly. While earthquakes and tornadoes both need strong foundations, tornadoes often require certain designs to mitigate the damage, while earthquake resistance relies more heavily on lateral-force-resisting systems and ductile behavior (2-5).

When looking to innovate, engineers often must adapt to things such as their materials, models, and designs. When improving their materials, engineers often use physical or digital models to compare one material to another. Models can also be improved with the use of AI, making these models much more realistic. These models can also compare designs to one another to find the best result (2-4, 6).

The main question this narrative review will be looking to answer is how structural engineers are adapting to current climate-based safety hazards. As mentioned before, climate change has increased the number of natural disasters happening and their destructive potential. Leading into this, innovation in these fields is more critical now than ever. This study is a narrative review focusing on three major hazards, fire, earthquakes, and tornadoes, and examines how

engineers are adapting to each of them through advances in materials, modeling, and design strategies.

## DEVELOPMENTS IN FIRE SAFETY, EARTHQUAKE SAFETY, AND TORNADO SAFETY

### Types of Hazards

#### Fire

There are multiple ways that a fire could start. For example, cigarettes are one of the most common causes of ignition; in one study, 5% of all fires were attributed to smoking materials. Heating equipment, such as fireplaces and water heaters are another major cause and represents the second leading source of residential fires. These fires typically occur when heating equipment malfunctions, contributing to nearly 40% of all structural fires. Electrical fires also fall into this category and can become dangerous due to overloading, poor electrical connections, or other failures. The growth rate of a fire depends on several variables, including building materials, building type, ventilation, and heat release rate (2, 3).

#### Earthquake Hazard

Earthquakes are mainly caused by the shifting of

tectonic plates, which are large sections of the Earth’s crust that move very slowly. There are multiple types of plate boundaries, which cause varying levels of power in earthquakes. Earthquakes are also caused by human activity, such as mining, and other natural causes, such as volcanic activity. Earthquakes are static in magnitude when it originates, but the ground motion intensity varies across locations and during the event.

Tornado Hazard

Tornadoes affect buildings differently than straight-line winds because of their highly rotational flow patterns. The tornado vortex introduces several interacting factors, such as suction, uplift, and debris impact, that make tornado-induced loads far more destructive than typical wind loads. Wind loads represent the forces exerted on a structure by moving air, and straight-line wind loads are generally much weaker than tornado loads. This distinction is important because the goal of engineering design is to reduce the vulnerability of structures to tornado-induced forces by strengthening the continuous load path (5, 7).

**Different Types of Innovations**

In structural engineering, we cannot look at just one innovation. There are several types of innovation that each have varying levels of importance, but are significant, nonetheless. Material innovations are innovations that include what a structure is constructed from, such as steel or concrete. Another important type of innovation is building design. These and material innovations go hand in hand, as materials allow design to thrive, and material effectiveness is only limited by the design. AI has become prevalent in recent years, and

structural engineering is no exception. AI is used for modeling to test designs and materials, among other things. These three types of innovations push forward structural engineering to make it what it is today through interacting with each other in different ways to improve natural hazard safety (Table 1).

Materials

Material innovations are a type of innovation that is often overlooked in regard to climate-based design. While implementing proper design is important, having materials strong enough to support the design is also crucial. Material innovation is also the main way engineers focus on performance-based engineering.

Performance-based engineering refers to focusing on a specific goal when engineering is important. One such type of performance-based engineering is resilience theory, which is how a building can recover after a disaster. One example of this is steel, which is not only an extremely durable material but also does not have a high cost in regard to financial burden. Steel excels at maintaining its shape through disaster while it can also rapidly recover. Concrete also provides an extremely strong material for foundational purposes, being durable and also conforming to the resilience theory (2).

When exploring different types of natural hazards, fire safety is the most material oriented. This is due to material durability mattering much more, along with thermal resistance being key to containing fires. These are much more performance oriented as they focus on mitigating damage taken rather than outright preventing it. This is due to human error being a major factor in many fires. These include materials such as fire-resistant gypsum and cement-based mortars, which are much

*Table 1. Comparative overview of material, design, and AI-based innovations across major natural hazard types.*

Hazard Type	Materials	Design	AI Modeling
<b>Fire</b>	Concrete, Steel, Composite materials, Shape-memory alloy, Fire-resistant gypsum, Cement-based mortars, Thermal barriers, Thermo-responsive polymers	Passive and active fire systems	BIM, Digital twin technology,
<b>Earthquake</b>	High-performance fiber-reinforced concrete, Shape-memory alloy, Steel, Advanced composites,	Base isolation, Energy dissipation techniques	BIM, Structural health monitoring systems, IoT, Digital twin technology
<b>Tornado</b>	Steel, Stronger materials, Shape-memory alloy	Roof-to-wall connections, Debris-resistant connections, Slanted roofs	Digital twin technology, IoT, BIM,

more durable against fire but still offer their basic needs in construction (2, 3).

Another type of material that has been increasing building adaptability is smart materials. Smart materials are materials that react to environmental stimuli, which allows the building to adapt to the type of hazard while maintaining structural integrity. A major material that is used in many of these innovations is thermo-responsive polymers. These types of materials can expand, contract, or fill in cracks depending on what is needed. These are also base materials in many other types of smart materials. 2 good examples of these use cases that are prevalent in every kind of safety are shape-memory alloy and high-performance fiber-reinforced concrete (HPFRC). These innovations are used to fill in cracks and revert to their original shape in the aftermath. These types of innovations are used across natural hazard safety due to their adaptability to every type of disaster. These innovations offer sustainability through their adaptability, allowing fewer resources to be used (2, 3).

### Design

Design is a type of innovation that focuses on infrastructure and resilience. Through maintaining building shape, the resilience theory is upheld, and design has become more sustainable through maintaining building integrity and conserving resources. Design has become more performance-focused in recent years due to buildings in different regions experiencing varying types of natural disasters.

A good example of this is through passive and active systems in fire safety. These systems focus on slowing down fires rather than stopping them completely. Passive systems do not require any form of activation to start. These are used in combination with materials above to ensure safety, while active systems require some form of activation to detect and suppress fire. These include sprinkler systems, smoke detectors, and heat detectors. These follow common resilience theory and performance-based design through focusing on containing damage rather than trying to contain and extinguish the fires outright (2).

As stated in an earlier paragraph, fire safety is mainly focused on materials. However, earthquake and tornado safety do not follow this pattern. These types of natural hazards are mainly mitigated by design, as materials do not greatly affect the outcome of these disasters. However, these two types of natural hazards have different focuses. While earthquake safety focuses more on foundational design, tornado safety focuses more on roof structure.

This is due to earthquake safety focusing on dealing with great foundational energy, while tornado safety focuses on redirecting wind loads to mitigate damage caused by tornadoes (4-7).

As seen in the contrasting types of design corresponding to each type, there are different types of designs. One type of design is base isolation. This is a technique where the building is technically off the ground using isolation bearings, which are placed between the ground and the building. These mainly focus on reducing structural damage, focusing on resilience, and performance-based design. Another technique used in earthquake-resistant engineering is energy dissipation techniques. These use dampers, which are objects that reduce vibrations and absorb energy in structures. There are several types of dampers, such as friction dampers and metallic dampers. These are mainly present for resilience and performance-based design (4).

Roof-to-wall connections connect walls and roofs to increase the roof's structural strength and connection to the home. This is due to slanted roofs often causing decreased wind load strength, but roofs get torn off amidst the intensity of a tornado. Roof-to-wall connections prevent this and reduce overall structural damage. Debris-resistant connections also apply this same concept but to other parts of the house, such as wall-foundation, garage door, etc. These follow performance-based design as they focus on the specific goal of redirecting wind loads off of the house. These types of innovations allow for more resilience and performance-based design through mitigating damage by specific means (6).

### AI Modeling

AI Modeling is the most recent innovation in modern structural engineering. AI modeling connects the worlds of material and design and allows for buildings to be monitored at all times. All types of natural hazards share the same AI modeling due to its widespread use cases across all types of hazards. AI modeling is unique as it is global rather than performance-based. Global design is a design that covers everything, rather than focusing on a specific thing like performance-based design does. AI modeling is much more globally designed for a few reasons. The first being AI is extremely advanced and can be utilized in a series of fashions, being able to fit all types of natural hazards. The second is that AI makes monitoring systems much more efficient than ever before (2-5).

A representative example of this comes in the form of digital twin technology. Digital-twin technology creates

highly accurate virtual models of buildings using real-world sensor data, providing real-time insights into building performance. AI can also be used to address specific natural disasters. One such example is SHM, or structural health monitoring systems. This actively checks structural health and gives live data. These innovations use sensors spread throughout the building to actively build models and simulate them using the data provided. This is known as IoT, or the Internet of Things. These innovations push global design through numerous systems, providing valuable information of the whole building, and being multifaceted through applying this information to models (2, 4, 5).

BIM is also a great example of global design. BIM stands for building information modeling, and it essentially merges all the data provided and puts it in an organized manner. This interacts with the innovations mentioned above through funneling the information and using the various components and advantages provided by each to form a wide array of accurate models. This builds upon resilience theory through focusing on keeping the entire building structurally intact in the moment in order to prepare for the future. Overall, AI modeling encourages global design and resilience theory (4, 5).

## **FUTURE DEVELOPMENTS AND IMPLICATIONS**

When considering how to innovate these fields, we must also think about long-term implications. Future-proofing structures are a key element of developing new technologies, as improving longevity can further reduce costs over time. Many challenges arise when engineering these innovations, and sustainability is one of the most significant. Engineers must consider not only the performance of materials but also their environmental impacts. Sustainability is increasingly promoted worldwide, and many nations now seek safety systems that are both effective and environmentally responsible. HPFRC is one example of a sustainable innovation: it reduces the need for steel reinforcement and can be produced using recycled composites. Climate change, a recurring theme in this paper, continues to intensify natural disasters and increase their frequency, pushing innovation to advance rapidly so that nations can keep up with growing hazard risks (1, 2, 4).

When observing material usage, several future-oriented technologies are emerging. Shape-memory alloys, for instance, can maintain structural integrity

longer than many conventional materials. Nanomaterials, extremely small-scale engineered particles, can also strengthen structures while reducing weight. These materials are often more sustainable and advantageous for long-term use. AI-based fire modeling, also known as predictive modeling, simulates how different materials, designs, or systems interact under fire conditions. This is useful for optimizing the placement of PFP systems or identifying weaknesses in materials.

When examining AI, technology and data play increasingly central roles. AI-enhanced simulations function similarly to AI fire modeling by optimizing structural designs and identifying potential weaknesses. Hybrid testing, which combines physical and numerical modeling, produces more accurate results and supports more realistic scenario simulations at reduced financial cost. Hybrid testing uses the data from systems such as SHM to test a building's current strength as well. Together, these AI-enabled tools help advance innovation, protect buildings, and support economic planning (2, 4, 6).

In tornado safety, the concept of loads is particularly important. Straight-line wind loads have much less impact on structures than tornado-induced loads. Structural forms can be manipulated to maximize straight-line load behavior; for example, slanted roofs help deflect tornado-induced forces and increase the proportion of straight-wind loads acting on the building. Shelters also play a critical role. Community shelters are essential for residents who do not have access to personal shelters, and their larger budgets often allow for stronger materials and more robust designs. AI models are increasingly being used to predict how tornadoes might move through a building or community, allowing engineers to develop more effective adaptation strategies (5, 7).

Interdisciplinary design is a critical component of advancing innovation across all hazard fields. Many nations are adopting interdisciplinary strategies because different fields can contribute unique insights and skills that may not exist within a single discipline. Global standards are also encouraged, as accommodating multiple regional codes can be challenging and may restrict the implementation of innovations. Variations in regional standards can create disparities in access to advanced technologies. Establishing global standards would streamline innovation by shifting focus to one unified set of guidelines rather than numerous conflicting ones. Inclusive innovation, strategies that involve a wide range of stakeholders, help strengthen collaboration

both internationally and within local communities. Engaging local communities can guide the placement of innovations and identify priority areas for implementation. Collectively, these strategies create an environment where innovation can thrive.

## **COMPARING AND CONTRASTING FIRE, EARTHQUAKE, AND TORNADO SAFETY**

When reviewing the literature, it is vital to explore the similarities and differences among fire, earthquake, and tornado safety. One important reason for this comparison is the potential for interdisciplinary design, as innovations developed for one hazard can sometimes be adapted for another. Although each field employs different design principles, they all strive for maximum resilience. Understanding how each principle functions individually allows us to identify where design strategies overlap. This is especially valuable because most regions of the world are at risk from multiple hazards. Determining where innovations can be integrated across hazards can reduce costs and create more efficient, multi-hazard-resistant infrastructure.

When comparing the fundamental forces at play, several similarities and differences emerge. Heat is the key destructive agent in fires, gradually weakening and degrading structural materials. In earthquakes, the primary force is ground motion, which shakes the structure and can compromise foundations, leading to collapse. Tornado risk centers on wind loads, particularly tornado-induced pressures that exceed typical straight-line wind loads. Engineering aims to redirect tornado-induced loads into more manageable straight-line loads wherever possible. When comparing these hazards, ground motion and wind loads share similarities because both are natural forces that cannot currently be replicated or controlled with modern technology. Heat, however, has a much higher likelihood of initiating a damaging event because it can originate from both natural and human-made sources.

Although the forces differ significantly, all hazard-mitigation strategies ultimately depend on two central elements: design and materials. However, each hazard prioritizes these elements differently.

Fire safety focuses primarily on materials, as structural design does not stop a fire, but material durability determines how long a building can withstand heat. Earthquake safety balances design and material considerations, as both strong foundations and ductile structural systems are required. Tornado safety

emphasizes design strategies such as load redirection and continuous load paths for residential buildings, while material strength becomes particularly important in community shelters and critical facilities (2, 4, 5).

Innovation across all three fields reveals interesting parallels. Data-driven and modeling-based methods show notable similarities. Digital-twin technology appears in fire, earthquake, and tornado research and is used to model building behavior under hazard conditions. AI modeling is also widely applied, though with different objectives: fire-based AI modeling evaluates material behavior and passive or active fire-protection systems; earthquake-based modeling analyzes both material and structural response and can isolate individual components; tornado-based modeling focuses on aerodynamic behavior, structural form, and load paths. Shape-memory alloys appear in both fire and earthquake engineering, though with different purposes, enhancing durability under fire exposure and contributing to self-centering or energy-dissipation mechanisms in earthquakes. Reinforced concrete is important in earthquake and tornado engineering, strengthening foundations and resisting force demands. Fire protection uses fire-retardant coatings and materials that improve resistance to ignition and heat damage. In terms of design, fire safety emphasizes protective systems rather than structural layout, while earthquake and tornado safety depend heavily on structural form, connectivity, and load paths (2-6).

Socioeconomic factors also shape progress in each field. More developed regions generally show greater advancements in fire and earthquake safety, while tornado safety tends to lag behind. This disparity arises partly from difficulty: tornado engineering is particularly challenging due to the extreme, localized, and often unpredictable forces tornadoes generate. Unlike fires, which progress more slowly, or earthquakes, which primarily affect foundations and structural systems, tornadoes impose intense pressure on every exposed element of a structure. As a result, many countries prioritize fire and earthquake safety over tornado-specific strategies. Additionally, the existence of community shelters can create a false sense of security, leading to fewer investments in tornado-resistant housing (4-6).

The gap between developed and developing countries further affects hazard resilience. Developed nations can invest more in advanced materials, monitoring systems, and code enforcement, while developing regions often lack the resources to go beyond minimum standards. This increases their vulnerability and results in higher

economic losses when disasters occur, widening the development gap. Fire hazards in particular are more common in developing countries due to inadequate infrastructure, outdated electrical systems, and limited regulatory oversight (3, 5, 6).

Integrated frameworks have the potential to unify hazard-specific engineering, climate resilience, and interdisciplinary research. Combining insights across fire, earthquake, and tornado engineering can streamline design practices and support more comprehensive hazard-mitigation strategies.

## **CONCLUSION**

From the literature review, several conclusions can be drawn. One of the most notable trends is the integration of AI into modern structural engineering. Through technologies such as digital-twin systems, AI modeling, BIM, and related tools, engineers can both model and monitor structures with increasing accuracy. Materials are also becoming more advanced and more focused on sustainability. Examples include shape-memory alloys and fiber-reinforced concrete, which offer improved performance under extreme hazard conditions. Design approaches in these fields are becoming increasingly performance-based, focusing on critical elements rather than the entire structure, which enhances hazard resilience (2, 3, 4, 6).

However, there are numerous limitations to implementing these innovations. One of the most significant barriers is cost. Many developing countries lack the financial resources to incorporate advanced technologies into all buildings, leaving many structures more vulnerable. Inadequate or outdated building codes in these regions further contribute to unsafe construction and insufficient hazard protection. Physical and environmental constraints also limit the implementation of innovations. The natural landscape, local soil conditions, and other environmental factors can complicate or delay new construction approaches. These constraints ultimately intensify the financial burden. Frameworks and regulatory systems present additional challenges because they differ widely across countries and regions. This inconsistency prevents certain innovations from being implemented globally and restricts the design freedom available to engineers (3, 4, 6).

On the technical side, several additional limitations emerge. Retrofitting older buildings is a major challenge because most structures that exist today were built

before many modern innovations were developed. Retrofitting requires substantial structural adaptation, which can be costly and, in some cases, technically infeasible. Data integration is another difficulty. Installing sensor networks or monitoring technologies in older structures is already challenging, and organizing and interpreting the large volumes of data generated by digital twin models or sensor systems can be complex. Interoperability also presents problems: many modeling and monitoring systems overlap in capability, leading to redundant information or overwhelming data streams that are difficult to process effectively (6).

Despite these challenges, several strategies can help overcome current limitations. Global collaboration is one of the most promising. Harmonizing engineering frameworks worldwide would dramatically reduce difficulties associated with adapting innovations to multiple regional codes. A unified framework would simplify design processes and make it easier to implement safety systems across different countries. Global collaboration would also facilitate the exchange of innovations, allowing nations with advanced safety technologies to support regions that lack such developments. Financial collaboration is also essential. A dedicated international fund supported by developed countries could help finance hazard-resistant construction in developing nations, reducing global inequality while strengthening international relations. For example, China's recent infrastructure investments in Nigeria illustrate how international cooperation can accelerate development while promoting diplomatic partnership. AI may also help address challenges related to interoperability and data management by organizing, filtering, and analyzing large datasets (6).

Balancing innovation with practical implementation will be essential for advancing hazard-resilient engineering. Engineers must consider not only how new technologies can improve resilience, but also how they can be realistically applied within diverse economic and environmental contexts. Understanding this balance will expand global access to innovation and help ensure that even less developed countries can adopt safer and more resilient infrastructure.

Despite these advancements, substantial progress is still needed to ensure that innovations can be widely implemented. Increasing support for developing countries, where limited financial resources and inadequate building codes heighten vulnerability to natural hazards is crucial in ensuring global hazard safety. Investment in these regions would not only

improve safety but also promote global equity in engineering innovation.

Overall, structural engineering has advanced rapidly, integrating technology, sustainability, and interdisciplinary methods to address modern climate-related challenges. As innovation continues, future developments will likely surpass the tools and methods available today, leading to safer, more resilient, and more sustainable infrastructure for communities around the world (3, 6).

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## CONFLICT OF INTEREST

The author declares no conflict of interest related to this work.

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