Summer Research Internship Program 2025

Mitigating Avalanche Destruction through CFD Modeling & Lattice-Structure Design

Supervisor: Prof. Manish Kumar
Department of Civil Engineering, IIT Gandhinagar

Submitted by:
Ayush Singh (21847719)
Department of Mechanical Engineering, Pandit Deendayal Energy University

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1. Abstract

Snow avalanches pose a serious life and infrastructure threat to mountainous areas. In this study, Computational Fluid Dynamics (CFD) is used to simulate the behavior of snow avalanches and analyze structural mitigation measures. Snow is simulated as a non-Newtonian Bingham plastic fluid to capture its behavior as a granular fluid. A CFD model is validated and applied with ANSYS Fluent 2025 to model snow impact on a vertical wall and validate the results with experiment, for both impact force and timing of impact. A lattice structure is then placed upstream of the wall to evaluate its potential in avalanche energy dissipation. The lattice-structure effectively minimizes the peak force of impact, which indicates decreased structural damage. This method illustrates the capability of combining CFD modeling and structural engineering to create resilient infrastructure in avalanche-prone locations. Ongoing research involves including deformable structures, multiple protective structures, and field-based terrain data for increased applicability.

2. Introduction

Snow avalanches are fast-moving, gravity-driven flows of snow and ice that pose a major natural hazard in mountainous, snow-covered regions around the world. Figure 1 shows a snow avalanche in the mountains capable of lot of destruction. Each year, they cause significant destruction, leading to around 250 fatalities globally, with about 1,900 deaths reported in Europe and North America between 2000 and 2010 alone [1]. Figure 2 shows destruction done by avalanches in the recent history. Avalanches not only endanger people engaged in recreational activities like skiing but also threaten roads, settlements, and critical infrastructure. Historical events such as the 1951 “Winter of Terror” in the Alps and more recent disasters in Italy, Afghanistan, and Pakistan highlight their destructive potential. Countries like Switzerland are highly prone to avalanches and are investing highly to reduce the number of deaths caused by avalanches. Effective risk reduction now relies on integrated approaches combining permanent structures, early warning systems, and land-use planning [2].

Figure 1: Depiction of snow avalanche [3]

Broadly, avalanches can be classified into dry-snow avalanche and wet-snow avalanche. Dry-snow Avalanches are caused due to overloading of an existing weakness in the snowpack. These mostly start after the snowstorms. Wet-snow avalanches happen when liquid water seeps through the snow cover. Typically, wet-snow avalanches release on their own. Unlike dry-snow avalanches, they cannot be purposely triggered. Wet-snow avalanches can occasionally inflict significant damage, but dry-snow avalanches typically result in the most avalanche fatalities, primarily among winter recreationalists [1].

Figure 2: Destruction caused by the snow avalanches (a) 29 people died when a hotel in Italy was hit by 60,000 tons of snow during an avalanche [4] (b) Destroyed mosque due to 1993 avalanche event in a village in Turkey [5]

There are two main ways that a snow avalanche might occur, either as a slab avalanche or as a loose fall. Loose flow avalanches, also known as point avalanches, occur when a little amount of snow fails and starts to travel and entrains more snow, causing the first failure. This process takes place in less volume than the slab avalanche. It looks like an inverted V-shaped avalanche extending outward as the snow mass descends. The majority of loose snow avalanches are harmless and compact. However, loose snow avalanches have the potential to entrain significant amounts of snow and wreak damage when the entire snow cover is saturated with water. Slab avalanches occur when a snow slab is released along a long plane of instability, caused by formation of ice by crystallization of snow during a sunny day. Slab avalanches account for the great majority of fatal avalanches and are the more dangerous of the two types because slab avalanches are more unpredictable than loose snow avalanches and usually involve more snow. [1].

Snow avalanches can be computationally modeled to predict their flow paths, enabling the avoidance of construction and human activity in high-risk areas. Additionally, modeling allows for the estimation of avalanche velocity and impact forces on specific terrains, which is critical for implementing preventive safety measures and optimizing the design of buildings and infrastructure to minimize potential damage. In the past, statistical and simplified models were commonly used, which are less accurate for complex scenarios [6]. With advancements in experimental data collection and computational capabilities, modern avalanche modeling has significantly improved, and Computational Fluid Dynamics (CFD) now offers a more precise and robust framework for simulating avalanche behavior.

A validated computational model was developed to simulate avalanche behavior and assess the effectiveness of protective structures under dynamic snow flow. The model provided a framework for estimating potential avalanche paths when applied to real terrains, thereby aiding in hazard assessment. It also enabled the analysis and optimization of structural interventions such as snow fences, snow nets, avalanche dams, retarding mounds, and supporting racks. These forms of protection have long been implemented in avalanche-prone regions, following practices established by institutions such as the SLF in Switzerland [7].

3. The objectives of the present study are as follows,

1. Simulate snow avalanche flow using Computational Fluid Dynamics (CFD) by modeling snow as a non-Newtonian fluid
2. To perform a mesh independence study for numerical accuracy
3. To validate the model with experimental results and verify with literature
4. To assess the effectiveness of lattice-based structures in reducing avalanche impact

4. Methodology

The whole idea of the study is to reduce the impact of the avalanche on structures by means of adding lattice-based structures down stream to the avalanche flow. To proceed, the first thing required to calculate the impact on the building is to develop a CFD-based model and simulate the flow of snow. To validate the CFD results against an experiment, the CFD model was developed replicating an experiment performed by Oda et al [8]. The snow was modeled as a non-Newtonian fluid to capture the behavior of snow effectively. The model of snow captured the granular properties of snow using partial-slip boundary conditions. The numerical model was implemented using a licensed version of Ansys Fluent 2025 R1 Software. Validation of the results with experimental and other numerical examples ensured the CFD model of snow. Upon validation, it allowed to add various lattice-based structures introduced in the flow path to study the flow of snow with the addition of these structures and impact on other structures.

5. CFD modeling

5.1 Snow Material Properties

Experiments done by Oda et al. suggested that the flow can be modeled as a Bingham Plastic fluid, which means that the snow will start to flow only when a certain amount of shear stress is applied on it. The expression for the viscosity of snow is experimentally found to be dependent on the dynamic viscosity, cohesion, static pressure and strain rate of the snow material as seen in the Equation 1. [8, 9].

$$\mu = \mu_0 + \frac{c + p\, tan\theta}{\dot{\gamma}} = \mu_0 + \frac{\tau_y}{\dot{\gamma}} \tag{1}$$

Further simplifications lead us to the Equation 2, where the dynamic viscosity is 2 Pa.s, the cohesion is 0, and the yield shear stress is 1 Pa, and to avoid singularity at very small strain rates, a minimum value of 10^5 Pa.s is used for the viscosity as suggested by Pala et al [9]. Figure 3 shows the shear stress vs strain rate graph for the snow model that is used for the simulations.

$$\mu = \min\left(10^5\ [Pa.s], 2\ [Pa.s] + \frac{1\ [Pa]}{\dot{\gamma}}\right) \tag{2}$$

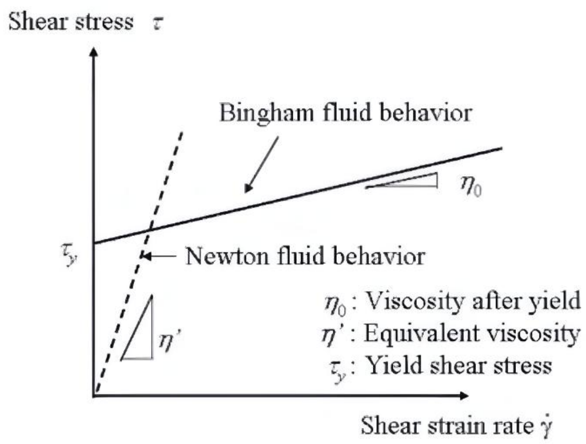

Figure 3: Shear Stress vs Strain Rate for the Bingham Plastic model of snow [8]

The density of the snow varies from 50 Kg m^{-3} to more than 500 Kg m^{-3}. In consistency with those experiments and models [8, 9], the snow model has a density of 500 Kg m^{-3}.

5.2 Computational Domain and Boundary Conditions

The study aims to replicate an experimental setup to make an accurate model first. Figure 4 shows the experimental setup where the box contains 883 N weight of snow. In this experiment, wall having load cells is used to calculate the impact force produced by the snow.

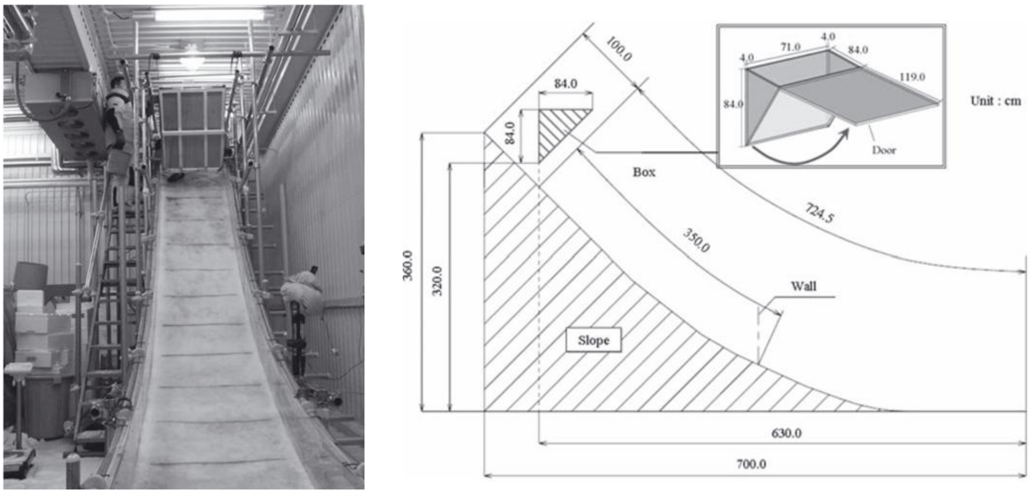

Figure 4: Experimental setup to be replicated in CFD model (a) Image of the experimental setup (b) Schematic of the setup showing the wall having load cells for impact measurement [8]

A virtual velocity approach was applied to model the boundary condition at the ground. The virtual velocity approach is a numerical method used to model partial slip at boundaries, especially in simulations involving granular flow or snow avalanches, where basal friction plays a significant role. Instead of directly imposing a velocity or a shear force at the wall, this method introduces a virtual velocity point outside the computational domain. This method allows to set the boundary condition as a function of fluid velocity instead of assigning a constant value.

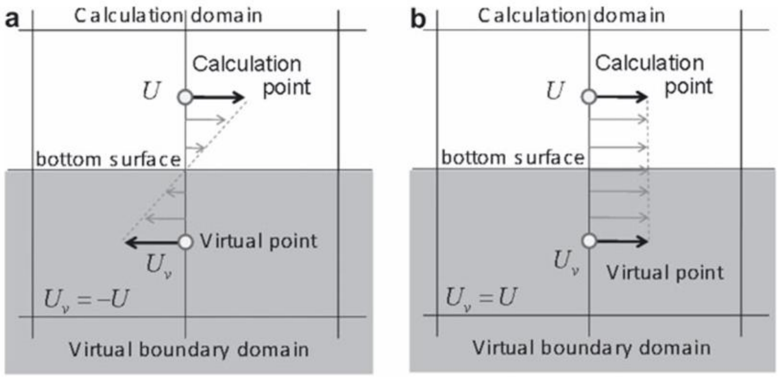

Figure 5: Use of virtual velocity to apply boundary condition (a) No slip condition (b) Full slip condition [8]

As shown in the Figure 5, to define the velocity at this virtual point, the Equation 3 is used:

$$u_v = -u(2\alpha - 1) \tag{3}$$

In Equation 3, u is the fluid velocity at a node (node 1) near the boundary, u_v is the virtual velocity assumed to be applied at a virtual node (node 2) outside the domain. It has to be noted that perpendicular distance between node 1 and boundary is same as that of node 2 and boundary, and the line joining node 1 and node 2 must be perpendicular to the boundary at that point. α is a partial slip coefficient ranging between 0 and 1. This coefficient controls the slip, when $\alpha = 1$, it corresponds to a no-slip condition (like a sticky wall), and when $\alpha = 0$, it represents full slip (no resistance at the boundary). For values between 0 and 1, the wall allows partial slip, depending on how much friction or resistance is present.

The velocity at the actual wall is then computed as the average of the internal and virtual velocities:

$$u_{wall} = \frac{u_v + u}{2} \tag{4}$$

For example, with $\alpha = 0.2$, the wall velocity becomes 80% of the nearby fluid velocity, simulating some slip due to moderate friction.

To connect this numerical slip coefficient to physical properties of the terrain, α is related to internal friction and basal friction angles through:

$$\tan\phi_b = \alpha \tan\phi \tag{5}$$

where ϕ_b is the basal friction angle, representing the roughness or frictional resistance of the surface (e.g., snow-covered ground), and ϕ is the internal friction angle of the flowing material. This allows one to use measurable or known material properties to compute α\alphaα and apply the appropriate boundary condition. $\phi = 30°$, $\phi_b = 5°$ and $\alpha = \frac{\tan(5°)}{\tan(30°)} = 0.1515$, and the wall velocity becomes about 85% of the adjacent fluid velocity.

In this case, this formulation is implemented using a UDF (User Defined Function) written in C++ for the ground boundary, while the other domain walls use symmetry conditions, which imply no shear stress and no normal flow. This virtual velocity method thus enables accurate modeling of basal interaction and energy loss due to friction in a physically consistent and computationally convenient way.

5.3 Meshing

The computational domain was discretized using a predominantly structured mesh with a maximum element size of 2.5 cm. The consistency in element shape and alignment of the mesh shown in Figure 6 ensures structured nature of the mesh. A structured mesh requires less memory and computational effort compared to the unstructured mesh. Due to simplified discretization in structured mesh, it also provides more accuracy than unstructured mesh,

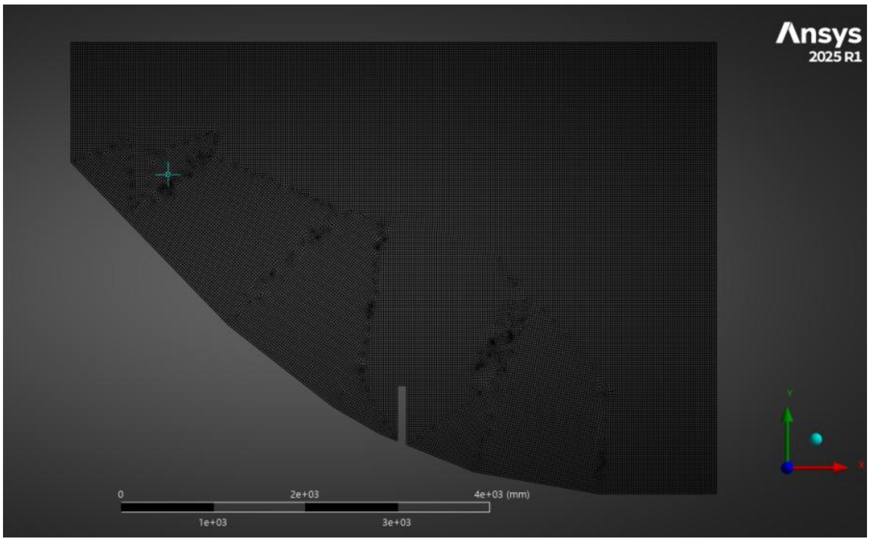

Figure 6: Mesh generated for the geometry

Mesh quality (Figure 7) was assessed using the element quality metric in ANSYS, which depends on the aspect ratio, skewness and orthogonal quality of the elements. The quality distribution, as shown in the figure, ranges from 0.390 (minimum) to 0.999 (maximum). The vast majority of the mesh lies in the high-quality range (above 0.9), indicating excellent element shape and low skewness throughout the domain. Lower quality elements, shown in orange and red, are localized and cover very less area which ensures that no crucial details will be missed. Overall, the mesh quality supports robust solution behavior and reliable results.

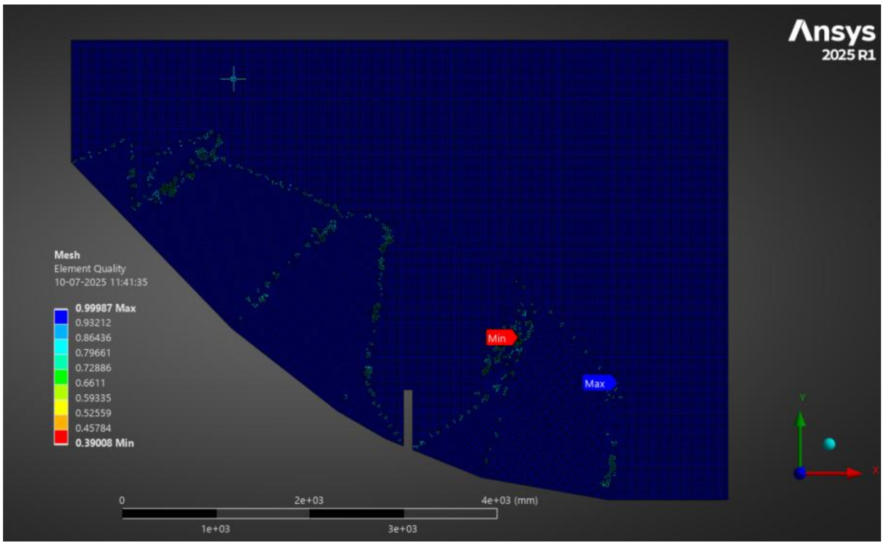

Figure 7: Mesh quality contour

5.4 Flow Regime and CFD Model

The flow in this study is assumed to be incompressible and laminar. Since the Mach number remains well below 0.3 throughout the domain, the incompressible assumption is justified. The flow is modeled as laminar, as for an external flow regime the local Reynolds number remains within the laminar range.

In this simulation, the interaction between snow and air is modeled as a continuous-continuous multiphase flow using the Volume of Fluid (VOF) method, where both phases are treated as immiscible fluids. This approach assumes that, within each computational cell, the two phases coexist, with each occupying a certain volume fraction. A cell would contain only single phase when the volume fraction of that phase is 1 and that of the other phase is 0. The method is particularly effective for flows involving a distinct but deformable interface, as it allows the volume fraction of each phase to evolve over time while solving a single set of momentum equations for the mixture. By doing so, the model captures the free-surface motion and phase interaction without requiring mesh deformation or interface tracking through separate domains. In Ansys Fluent, the use of Geo-Reconstruct scheme the sharpens the interface between snow and air, ensuring realistic prediction of the flow front, splash effects, and impact dynamics. Table 1 shows the summary of the CFD model of snow.

The governing equations of the 2-phase VOF flow are:

1. Navier-Stokes Equation (Momentum Conservation)

$$\frac{\partial \boldsymbol{u}}{\partial t} + \mathbf{u}.\nabla \boldsymbol{u} = -\frac{1}{\rho}\nabla p + \frac{\mu}{\rho}\nabla^2 \boldsymbol{u} + \boldsymbol{g} \tag{6}$$

2. Continuity Equation (Mass Conservation)

$$\frac{\partial \alpha_q}{\partial t} + \nabla\left(\alpha_q \boldsymbol{U}_q\right) = 0 \tag{7}$$

3. Volume-Fraction Equation

$$\sum_{\{q=1\}}^{N} \alpha_q = 1 \tag{8}$$

Table 1: Solver Settings for the CFD model [9]

Solver Setting	Value / Method
Solver Type	Pressure Based, Transient
Flow Type	Laminar (No Turbulent Model)
Pressure-Velocity Coupling	Semi-Implicit Method for Pressure Linked Equations
Pressure Discretization	PREssure STaggering Option (PRESTO!)
Momentum Discretization	Second Order Upwind
Transient Formulation	First Order Implicit
Multiphase Model	Volume of Fluid (VOF)
VOF interface Discretization	Geo-Reconstruct
CFL Number	2 (Acceptable accuracy for an implicit model)
Software	Ansys Fluent 2025 R1

6. Results and Discussion

6.1 Validation of the CFD model

The CFD model was validated by comparing its results with experimental data for snow impact force on a wall. Figure 8 shows the snow flow progression at different time steps. The snow, represented by the red phase, moves down the slope and strikes the vertical wall, deforming over time.

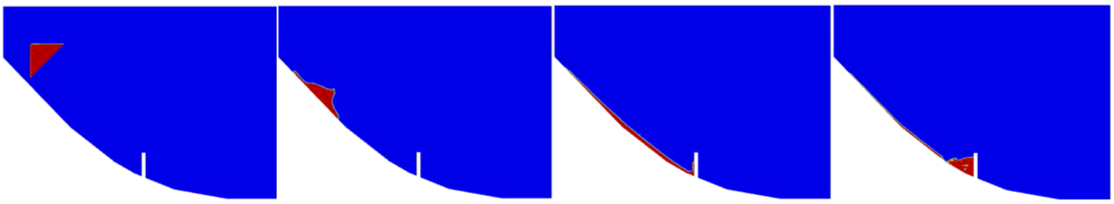

Figure 8: Figure 6: Snow profile contour at different time steps (a) 0 s (b) 0.5 s (c) 1 s (d) 2 s

Figure 9 presents a comparison between the impact force predicted by the CFD model and the experimental results obtained by [8]. The CFD model captures both the magnitude and the timing of the peak impact force with 4.9% accuracy in peak impact force and 1.6% accuracy in timing of peak impact. The initial rise and oscillations observed in the numerical result are consistent with the experimental trend, demonstrating that the model effectively replicates the transient response during the snow-wall interaction. Minor deviations in peak value and fluctuations can be attributed to simplifications in the numerical setup and assumptions like perfect laminar flow, uniform material properties and using the ground boundary condition to capture the granular behavior of snow. Overall, the close agreement between simulation and experiment validates the capability of the developed CFD model to simulate real-world snow impact dynamics reliably.

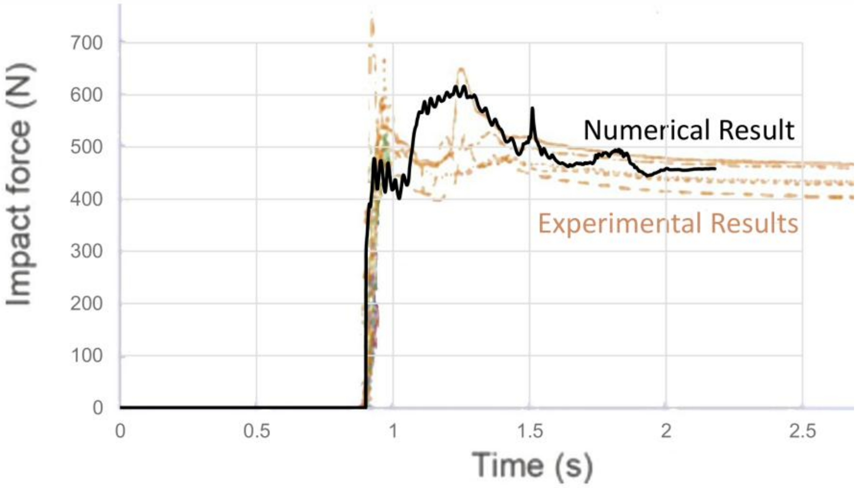

Figure 9: Comparison of CFD results with the experimental values of impact force calculated on the wall

6.2 Introducing a Lattice-Based Structure

To investigate the potential of mitigating the snow impact force, a lattice-based structure was introduced into the simulation domain, as shown in Figure 10. The lattice is modeled as a rigid, stationary structure, positioned upstream of the wall to interrupt and deflect the flow of snow. The lattice structure is having 65.36% of space in the structure to let the snow move through. The idea is to simulate how such protective structures, when integrated into mountain infrastructure or building designs, can reduce the sudden force exerted by snow avalanches.

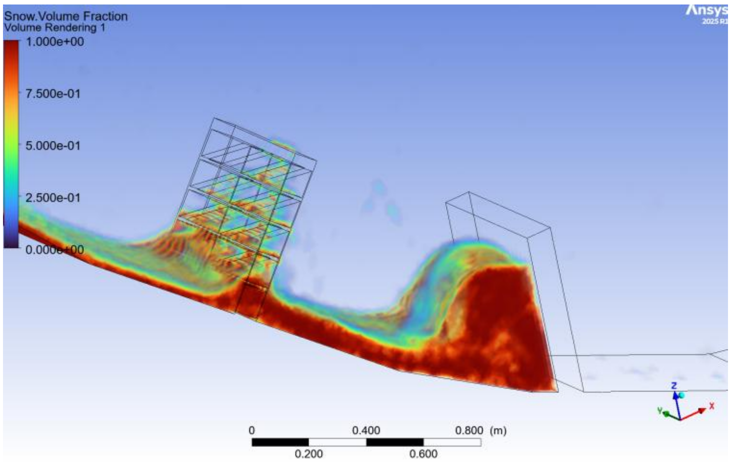

Figure 10: Volume Rendering of the snow with lattice structure

The comparison of impact forces, shown in Figure 11, demonstrates the effectiveness of the lattice. In the "Without Lattice" case, the impact on the wall is abrupt and peaks sharply, indicating a higher strain energy transferred to the wall compared to the “With Lattice: case. Although both curves eventually converge to a similar value, corresponding to the weight of snow statically pressing on the wall, the difference lies in the initial impact. A sudden impact introduces high strain energy, increasing the likelihood of cracks, deformations, or collapse. In contrast, the reduced and delayed force due to the lattice leads to lower energy absorption demands on the wall, improving the safety and longevity of structures in avalanche-prone regions.

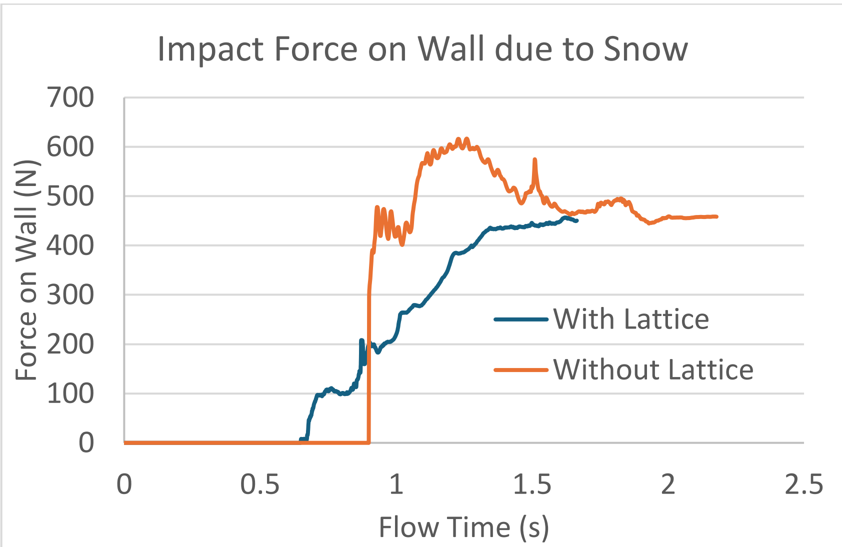

Figure 11: Effect of Lattice Structure on the impact force on wall by the snow

The results suggest that protective elements like lattice structures can significantly improve resilience against snow-related natural hazards.

7. Future Work

The current study demonstrates the effectiveness of a single rigid lattice structure in reducing the impact force of snow on a vertical wall. However, there is significant scope for further enhancement and realism in future simulations. One key direction is the use of multiple lattice structures arranged strategically along the slope. These structures can be designed not only to absorb but also to deflect and redirect the snow flow, further reducing the momentum transferred to critical infrastructure. An optimization study can be conducted to determine the most effective number, spacing, and placement of such structures to maximize protection while minimizing material usage.

Another major extension is to include Fluid-Structure Interaction (FSI) modeling. In the current study, the lattice was assumed to be rigid, but structural components deform under impact. Incorporating FSI will allow the simulation to account for material properties, deformation, and dynamic response, enabling more accurate predictions of stress distribution and potential failure. This can guide the selection of materials, cross-sectional dimensions, and structural reinforcement required for actual deployment.

Lastly, to increase the applicability of the simulation results, the model can be extended to real-world terrain data and large-scale snow volumes. Incorporating high-resolution topographic maps and site-specific avalanche paths will enable realistic avalanche scenario modeling, improve hazard assessment and supporting better-informed engineering and policy decisions for avalanche-prone regions.

8. Conclusion

This study successfully demonstrates the application of CFD modeling using the Volume of Fluid (VOF) method to simulate snow impact on structures and assess mitigation strategies. The numerical model was validated against experimental data, showing good agreement in both the timing and magnitude of impact forces. The simulation captured the dynamic behavior of snow flow, including free-surface deformation and impact on vertical walls. A lattice-based structure was introduced to study its effect on reducing impact force. Results showed that the lattice significantly reduced the peak force and transformed the abrupt impact into a more gradual load, thereby decreasing the strain energy absorbed by the wall. This reduction in impulsive loading can play a critical role in minimizing structural damage during snow avalanches. Overall, the model provides a reliable framework for evaluating protective designs and serves as a foundation for future work involving optimized structures, deformable materials, and real-world terrain modeling for avalanche mitigation.

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