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We are proud to present the June issue, Vol. 11 of our online journal MIJST, which focuses on the cutting edge of technical excellence and its profound effects on our lives. We encourage you to go through the virtual halls of technical excellence, where engineers from all over the world congregate to collaborate, inspire, and alter the world we live in, as part of our unrelenting dedication to expanding the limits of human achievement. Together, let's use engineering to pave the way for a better, more intelligent, and more sustainable future.

I would like to take this opportunity to thank the editorial team of the journal for all of their efforts in creating the current edition. My deepest gratitude is extended to all of the reviewers of the papers in this issue for their priceless recommendations and remarks. All of the National and International Advisory Board Members of MIJST have my sincere gratitude for their constant advice and recommendations aimed at raising the caliber of MIJST.

Brigadier General Md Wahidul Islam, SUP, ndc, psc
Acting Commandant, MIST, Bangladesh
Chief Patron, MIJST, Bangladesh
The June 2023 issue has been published on time. I want to thank the production team, editors, reviewers, and authors for making this possible.

Together with the editorial and advisory board members, we are firmly committed to getting the MIST International Journal of Science and Technology (MIJST) indexed in SCOPUS, Web of Science (WoS), Emerging Source Citation Indexing (ESCI) by Thomson Reuters/Clarivate Analytics, and the Directory of Open Access Journals (DOAJ) within the allotted time frame. Several databases have indexed the MIJST, including Google Scholar, DOI Crossref, Microsoft Academic Search, Semantic Scholar, Publons, Creative Common, BanglaJOL, and the Open Journal system.

I humbly ask that you all submit to our journal any scholarly works that are unpublished, unique, and inventive in any area of science, engineering, technology, or allied subjects. All submitted contributions are subject to a double-blind peer review procedure with useful input to ensure quality, originality, and innovation.

The current (June 2023) issue incorporates six original research articles dealing with the effectiveness of non-motorised vehicles on spatial extent for transit-oriented development, heat input effect on wire-arc additive manufactured steel structures, a zero equation model for external aerodynamics, numerical modelling of low-velocity impact on woven polymer composites, the impact of stress and temperature-dependent rock's permeability for underground nuclear waste disposal, and the prevalence of multidrug-resistant Salmonella in raw salad vegetables. Each of the six articles discusses a relevant issue.

I sincerely appreciate the dedication and hard work of the Journal team, which includes the Chief Patron, Executive Editor, Associate Editors, Section Editors, Reviewers, Editorial and Advisory Board Members, Proofreaders, and Web Production Consultant.

My heartfelt plea to all of you is that you spread the word about the MIST International Journal of Science and Technology (MIJST) to your colleagues, academics, research students, and librarian liaisons.

I openly welcome your valuable comments, ideas, and suggestions. Please call me at +61 3 99256103 or email me at firoz.alam@rmit.edu.au or mijst@mist.ac.bd.

Sincerely,

Prof. Dr. Firoz Alam
Editor in Chief
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Measuring Effectiveness of Non-Motorized Vehicles on Spatial Extent for TOD Development: A Case Study for MRT 6 in Dhaka

Md. Anwar Uddin1* and Md. Shamsul Hoque2
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Abstract
To improve the effectiveness of conventional walking-based Transit-Oriented Development (TOD), introducing Non-Motorized Vehicles (NMV)-based TOD will be a more efficient alternative since it will increase the spatial extent of the TOD node’s buffer area. This paper discusses the available Bicycle-based TOD (BTOD) concept. Based on this concept, the spatial extent of NMV-based TOD (NTOD) has been calculated. A trip-based survey has been conducted on the selected regions of Dhaka along the line of MRT 6 regarding who uses NMV (Rickshaw, Bicycle) and public transport (PT) for his daily commuting. A trip chain analysis was performed first to capture the trip pattern of daily commuters. From the trip chain analysis, it has been found that PT-based trip chains dominated the city’s entire trip chain. Consequently, it has also been found that walking-only and walking-NVM accessible trips dominate 32% and 23% of the entire PT trip chains. However, based on the findings of trip chain analysis to calculate the spatial extent by developing regression models, it has been observed that the access trip length for walking ranges from 1.2-1.4 km, whereas the access trip length for NVM ranges from 4.5-4.7 km. In Dhaka, the catchment area of NTOD can increase the accessibility potentially by spatial extent expansion of about 70% from the conventional TOD. Therefore, it can be inferred that NVM will give more spatial accessibility than walking. As a result, a new window of planning and design strategies will be opened for the planners and policymakers around TOD station area planning considering NMV. Along with strategic recommendations, limitations, and future research agendas have also been discussed in this paper.

Keywords: Transit-Oriented Development, Trip Chain, Public Transport, Non-Motorized Vehicle, Spatial Extent

1. INTRODUCTION
Transit-oriented development (TOD) is a planning idea that promotes using public transport (PT). It efficiently combines land use and transportation planning (Deng et al., 2022). Calthorpe (1993) describes TOD as a “Pedestrian Pocket,” “Compact Neighborhood Development,” or even an “Urban Village.” According to Bertolini (1999), public transportation is the spine of the transportation system in TOD, with strategically placed transit stations.

However, TOD has some advantages over other urban planning strategies. Such as, the TOD framework reduces motorized journeys, increases the share of non-motorized travel, and decreases travel distances, reducing automobile occupancy levels (Cervero & Kockelman, 1997). Furthermore, it is imperative to mention that decades of auto-dependency have brought adverse upshots such as traffic congestion, noise, poor health, and reduced social life, hindering sustainable development (Cervero, 2002; Cervero & Dai, 2014; Cervero & Day, 2008; Curtis & Scheurer, 2017). So, TOD is contrary to conventional auto-dependent growth. Further studies show that well-planned and designed communities and neighborhoods benefit from making public transit accessible and bicycling and walking more convenient (Samimi et al., 2009). However, the fundamental concept of TOD supports sustainable development (Li & Lai, 2009) by promoting economic, environmental, and social sustainability (Uddin et al., 2023).

Although some advantages are discussed above, conventional TOD has several criticisms. Firstly, reduced haphazard urban sprawl and enhanced density are required...
to foster transit ridership in TOD. However, such interferences will subdue the station’s surroundings’ quality of life and integrity (Lin & Gau, 2006). Secondly, adequate density must be promoted for TOD growth in the core of the cities. Therefore any stratified and medium-density or hybrid construction inducing density becomes challenging to reshape this growth (Nelson & Niles, 1999). Thirdly, according to Uddin et al. (2023), density should be the primary indicator for TOD planning in a developing city like Dhaka. However, density is often defined by the number of people who use a transit station. Especially in non-core areas, passenger transit load is considered the most critical factor (Jin et al., 2023). Nevertheless, the dwelling unit is vital in demand for transit use to supply PT in that region. According to Calthorpe (1993), at about 2,000 sq. ft per acre, the housing unit has a moderate to high density, proving PT will effectively promote the TOD. However, similar PT service in places with low travel demand yet high dwelling unit exits is impracticable because no relevant areas can be developed (Black, 1996).

Therefore, the conventional TOD’s weaknesses should be addressed for sustainable planning and development. So, a new Bicycle-based TOD (BTOD) concept has been introduced, addressing all the criticisms of walking-based TOD. It amalgamates the conventional TOD design and cycling, creating a station-oriented layout and location. There are some advantages of BTOD to conventional TOD. Firstly, The BTOD is competent in hoisting transit ridership. Secondly, the catchment area of BTOD can be 36 times larger than conventional TOD. Therefore, BTOD is reasonably applicable and feasible even for a relatively small population in an over-developed area. Finally, BTOD enjoins spatial and functional reconfiguration of the right-of-way (Lee et al., 2016).

In the TOD framework, active travel is the influencing factor. Active travel typically includes walking and cycling, positively influencing health and environmental prospects. For example, a study by Xiao & Wei (2023) reveals that more retail facilities attract walking-based trips. In contrast, more dwelling units generate bicycle-based trips. Therefore, TOD can use walking and bicycling as principal access modes. Access mode plays a vital role in achieving the principles and goals of TOD. However, TOD will capture more ridership through densified development and high land use mixedness; conversely, it will also degrade the livability of the node areas and exacerbate congestion. Therefore, to balance the standard of living and ridership, access distance should be extended for TOD planning, which may not be achievable only by walking. Moreover, proper access modes improve connectivity between transit nodes and multi-modal hubs, which is one of the critical factors in equitable TOD planning (Chen et al., 2022). Therefore, discovering other access modes and introducing a new concept based on BTOD are the primary contributions of this research.

Therefore, based on BTOD, we want to introduce a new Non-Motorized vehicle based TOD (NTOD) concept in this research. There is a reason to choose this new concept where NMV is the access mode for TOD hubs. (JICA & DTCA, 2015) study reveals that “Walking” is the primary means of transportation for low-income groups, whereas “Car-sharing” is more popular as income increases. “Bicycle” and “Motorcycle” have little overlap in either of the groups. This study also depicts that “Bus” is chosen for long-distance travel while “Walking” and “Rickshaws” are best suited for short-distance travel, which shows us potential access modes to TOD nodes. Moreover, as a sustainable mode of transport, this research focuses on incorporating a rickshaw with the bicycle termed NMV mode in Dhaka city. However, spatial extent measurement is very critical for BTOD planning and implementation. Access to public transportation can be measured by the access distance of the access mode, i.e., bicycle for BTOD. Some studies have been conducted on measuring and fixing bicycle access distance. These studies suggested different methodologies to measure access distance for developed countries. Rastogi & Rao (2003) conducted a study in India, our neighboring country. They measured the access distance of bicycles for PT, and they proposed it between 1.8 km and 4.07 km for Mumbai, India. As access distance between bicycles and PT has been measured by different methods, measuring access distance between NMV and PT in Dhaka should have a proper method.

In this research, we have taken the corridor along Mass Rapid Transit (MRT) line 6 in Dhaka, one of the world’s most densely inhabited cities. Almost 17 million people live here, rising to 20 million by 2030 (TYPSA, 2020) and 30 million by 2035 (World Bank, 2019). In Bangladesh, most living amenities and jobs are based in Dhaka, making Dhaka a significant area for human migration. Around 38.7% of the Dhaka population were migrants recently from other countries. Therefore, to make Dhaka a sustainable city, Five MRT lines and two BRT lines have been proposed, and among them, MRT 6 and BRT 7 are in the construction stage (JICA & DTCA, 2015). Moreover, ten MRT/BRT hubs and four multi-modal hubs have also been proposed with high TOD potential (TYPSA, 2020).

In this paper, the resolution of the spatial extent of NTOD will be entwined in some significant acumen. Firstly, based on the bicycle’s spatial extent (access distance), a methodology will be developed for measuring the spatial extent of NMV. Secondly, measurement of the access distance of NMV will be performed by developed regression models. Consequently, a comparison with the spatial extent of the walking will be conducted based on measured access distance. Finally, recommended policy guidelines for NTOD node planning will emerge based on the measured spatial extent.

2. METHODOLOGY

A. Study Area

In this research, MRT 6 has been selected as a study area (Figure 1) for developing models of the spatial extent of walking and NMV. MRT 6 has 17 nodes or stations. As the stations of MRT 6 are not operational yet, we have taken the spatial extent of PT as a shadow for the nodal spatial extent.
of MRT 6. This analysis will explain the spatial extent of the walking and NMV. These ideas will be convenient for node-based accessibility of TOD. Moreover, if we get an idea about accessibility before the operation of transit hubs, more secondary route development with more station access can be implemented parallely, which will be a helpful tool for policymakers and planners.

![Figure 1: MRT Line 6 with 17 Stations as Study Area (DMTCL Website)](image)

**Figure 1:** MRT Line 6 with 17 Stations as Study Area (DMTCL Website)

### B. Data Collection

The spatial extent of entry and egress trips for PT has been analyzed through questionnaires (500 samples) along the corridor around the 17 nodes of MRT 6, Dhaka. The survey was conducted between March to April 2020. In the survey, both NMV users and non-NMV users were interviewed randomly. Questions frequently asked during the survey included the transfer, current transport routes, and access mode from home, transfer time, entry distance, and exit distance. A detailed questionnaire survey has been depicted in Table 1.

**Table 1**
The main questions asked during the survey

<table>
<thead>
<tr>
<th>No.</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regular traveling/commuting purposes?</td>
</tr>
<tr>
<td>2</td>
<td>What is your regular mode of travel?</td>
</tr>
<tr>
<td>3</td>
<td>What is your secondary mode of travel?</td>
</tr>
<tr>
<td>4</td>
<td>What combination of travel modes do you usually use?</td>
</tr>
<tr>
<td>5</td>
<td>What access mode do you use from home?</td>
</tr>
<tr>
<td>6</td>
<td>What egress mode do you prefer from the bus station?</td>
</tr>
<tr>
<td>7</td>
<td>What is the approximate distance to your public bus station from your home if you use public transport?</td>
</tr>
<tr>
<td>8</td>
<td>If you use public transport, what is the approximate distance of the public bus station to ride from your educational institute/other job-based locations?</td>
</tr>
<tr>
<td>9</td>
<td>Willingness to use NMV?</td>
</tr>
<tr>
<td>10</td>
<td>What reason for using NMV as an access mode?</td>
</tr>
</tbody>
</table>
C. Analysis Approach
As our primary purpose of this research is to measure the access distance of NMV, the arrival cumulative percent graph (Figure 2) was used in this case. Hino et al. (2000) advocated this for the first time to map the accessible PT station area’s spatial extent. Here, Ki is defined as the accessibility indicator in cumulative percent (Eq. 1).

\[ K_i = \int_{0}^{D} A \times x \, dx \]  

(1)

Ki denotes the average distance a commuter can reach at the nodes in a specific period. To compute this number, it is necessary to determine the geographical extent of distance or time. However, the current study employed boundary value instead of the average value to the approximate spatial extent or the marginal distance. When determining the overall cumulative percentage of access, the essential element is the percentage of persons who have arrived thus far, not the average arrival. That is why developing a cumulative percent graph is one of the critical factors in this research.

In the final part of this research, regression models were developed to determine the access distance where x and y variables were used as access distance and cumulative arrival distribution percent, respectively. As the commuter access to or egress from the stations are part of a different trip chain, a trip chain analysis was also conducted to find support for rationale of choosing NMV over walking as access mode. Moreover, it is predicated on the idea that passengers can enter or exit a trip chain from either the destination or the point of origin at a PT stop (Lee et al., 2016).

Finally, access distance for walking and NMV was measured using the developed regression model and applying the cumulative trip distribution that meets the 85th percentile of the total. In this case, the dependent variable (y) was fixed as 85%, and the access distance (x) was calculated from the most statistically significant regression model. A comparative study between the conventional TOD and NTOD was conducted with the measured access distance using the geographic information system (GIS) by developing buffer maps. Moreover, we did not confine our study to only the spatial spectrum of TOD. Our research was also conducted on cost-effectiveness, congestion perspective, and land value capture of NTOD to prove that the NTOD would perform better than conventional TOD. Therefore, NTOD can be implemented in Dhaka shortly.

3. RESULTS AND DISCUSSION
A. Trip Chain Analysis
A trip chain analysis has been conducted to evaluate the spatial extent of the modes of walking and NMV (i.e., Bicycle and Rickshaw). From various responses, 25 categories of the trip chain have been identified along the MRT 6 of Dhaka. The trip chain analysis shows that the PT-based trip chain dominates the entire trip chain in the study area. Therefore, the PT-based trip chain has been studied for research purposes. However, on the other hand, the whole trip chain analysis aims to see whether our research purpose is justified. Hence, walking and NMV-accessible PT-based trip chains are the most common and dominant.

Nine categories of all PT-based trips have been depicted in Table 2 below. In addition, it has been discovered that 32% of the entire PT trip chains are dominated by only walking-accessible PT trip chains (Home→Walking→PT→NMV→Destination).

<table>
<thead>
<tr>
<th>Trip Chain Type</th>
<th>PT Based Trip Chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>Home→NMV→PT→NMV→Destination</td>
</tr>
<tr>
<td>Type 2</td>
<td>Home→NMV→PT→NMV→Walking→Destination</td>
</tr>
<tr>
<td>Type 3</td>
<td>Home→NMV→PT→Walking→Destination</td>
</tr>
<tr>
<td>Type 4</td>
<td>Home→Walking→NMV→PT→NMV→Destination</td>
</tr>
<tr>
<td>Type 5</td>
<td>Home→Walking→NMV→PT→NMV→Walking→Destination</td>
</tr>
<tr>
<td>Type 6</td>
<td>Home→Walking→NMV→PT→Walking→Destination</td>
</tr>
<tr>
<td>Type 7</td>
<td>Home→Walking→PT→Leguna→Walking→Destination</td>
</tr>
<tr>
<td>Type 8</td>
<td>Home→Walking→PT→NMV→Destination</td>
</tr>
<tr>
<td>Type 9</td>
<td>Home→Walking→PT→Walking→Destination</td>
</tr>
</tbody>
</table>

As our main study concerns walking and NMV modes for accessibility with PT, there is a need for further individual investigation of these modes. We have observed that 39% of the walking-based PT access trip is contributed by the Home→Walking→PT→Walking→Destination trip chain, in which entry and egress trips are contributed by walking (Figure 3(a)). However, 34% of NMV and PT-based trips are contributed by the Home→Walking→PT→NMV→Destination trip chain (Figure 3(b)).

B. Developing Cumulative Percent Graph
The final purpose of this investigation is to discover the level of access required. This approach, however, is unwieldy since it only averages out the access distances and fails to consider the unequal distribution of these distances. Therefore, for establishing a regression model, users'
distribution and cumulative ratio were calculated for variable x (spatial extent) and evaluated using the findings y (cumulative percent of frequency). In the initial phase, the ‘y-value’ is quite sensitive; however, the access distance level is limited at the end, so the ‘y-value’ becomes less critical. Therefore, cumulative percentages for entry and egress walking and NMV-based trips have been developed. Based on that graph, the regression model has been developed to get the spatial extent of both access modes. Here, PT is considered a shadow access point. Figure 4 shows the cumulative percentage of walking and NMV-based entry and egress trips.

Figure 3: Percent of PT Based Trip Chains for (a) Walking and (b) NMV

Figure 4: Cumulative Percent vs. Spatial Extent Curve for (a) Walking Based PT Entry Trip, (b) Walking Based PT Egress Trip, (c) NMV Based PT Entry Trip, and (d) NMV Based PT Egress Trip
C. Developing Regression Model
A cumulative trip distribution was utilized at least 85th percentile of the total to determine the access distances to the station. In other words, the value of y (cumulative percent) was set to 85 percent, and the value of x (spatial extent) was generated. Five regression models have been developed: Linear, Quadratic, Cubic, Logarithmic, and S-curve. All models are statistically significant. These five types of regression models have been seen in Figure 5, where four types of PT trips have been classified.

The cubic model is the best regression model for PT-based entry and egress trip spatial extent (Table 3). For example, the $R^2$ value for a walking-based PT entry trip is 0.968, the best among all other models of this type of trip. However, these values for walking-based egress, NMV-based entry, and egress trips are 0.985, 0.962, and 0.991, respectively.

![Figure 5: Cum. Percent vs. Spatial Extent of (a) Walking Based PT Entry Trip, (b) Walking Based PT Egress Trip, (c) NMV Based PT Entry Trip, and (d) NMV Based PT Egress Trip](image)

Table 3: Regression Models of Spatial Extent of Different Walking and NMV Based PT Trips

<table>
<thead>
<tr>
<th>Regression Model</th>
<th>$R^2$</th>
<th>$F$</th>
<th>Sig</th>
<th>Type of Regression Model</th>
<th>Type of Trip</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y = -18.322x^3 + 26.830x^2 + 69.52x - 4.785$</td>
<td>0.968</td>
<td>212.077</td>
<td>0.000</td>
<td>Cubic Model</td>
<td>Walking Based PT Entry Trip</td>
</tr>
<tr>
<td>$y = -2.855x^3 - 9.610x^2 + 78.032x + 4.069$</td>
<td>0.985</td>
<td>363.212</td>
<td>0.000</td>
<td>Cubic Model</td>
<td>Walking Based PT Egress Trip</td>
</tr>
<tr>
<td>$y = 0.249x^3 - 5.602x^2 + 41.209x - 5.818$</td>
<td>0.962</td>
<td>152.201</td>
<td>0.000</td>
<td>Cubic Model</td>
<td>NMV Based PT Entry Trip</td>
</tr>
<tr>
<td>$y = 0.175x^3 - 4.390x^2 + 37.332x - 11.986$</td>
<td>0.991</td>
<td>751.433</td>
<td>0.000</td>
<td>Cubic Model</td>
<td>NMV Based PT Egress Trip</td>
</tr>
</tbody>
</table>
Moreover, we have two equations of the spatial extent of walking as secondary access mode from regression model analysis. First, the spatial extent for walking-based entry and egress trips is 1.2 km and 1.4 km. Similarly, for NMV-based entry and egress trips, it is 4 km and 4.7 km.

From the spatial extent measurement by developing regression models, we have found that the access trip length for walking ranges from 1.2-1.4 km, whereas the access trip length for NMV ranges from 4-4.7 km. So, it has been found from the research that NTOD can increase the accessibility potentially by spatial extent expansion of about 70% for MRT 6 in Dhaka.

Figure 6 shows a spatial comparison of nodal buffer based on the access distance of the walking and NTOD. The spatial extent of walking covers 15% to 18% of Dhaka, whereas the spatial extent of NMV covers 51% to 58% of Dhaka. So, from this analysis, it can be inferred that NMV-based accessible modes will give more spatial accessibility than conventional walking-based accessible modes.

Figure 6: Comparative Visual Representation of Nodal Spatial Extent of MRT 6 for (a) 1.2 km buffer, (b) 1.4 km buffer, (c) 4 km buffer, and (d) 4.7 km buffer
The significant findings of this research are that the estimated access distance from home to station and station to work is 1.2 km and 1.4 km, respectively, for walking. On the other hand, the access distance for NMV from home to station and station to work is 4 km and 4.7 km, respectively. A study by Lee et al. (2016) found that a bicycle’s access distance for Daejeon city in Korea was 1.96 km to 2.13 km. This is almost the access distance of NMV in Dhaka. That means an NMV covers more spatial distance in Dhaka than in other cities.

Moreover, Daejeon is a mono-centric city, and Dhaka is a polycentric city. For a polycentric city, travel distance is typically higher (Su et al., 2021) than in a monocentric city. So spatial coverage goes higher. As Lee et al. (2016) found, there is a massive potential for BTOD in Daejeon. Therefore, NTOD will be more effective for Dhaka. Moreover, for Daejeon city, the catchment area was 12.06 km² which was 11 times higher than the conventional TOD of Daejeon city. Whereas for Dhaka, the catchment area for NTOD covers 50.27 km² to 69.4 km², which was more than 11 times higher than the conventional TOD of Dhaka.

Moreover, considering the hypothesis that NTOD will be enhanced by choosing NMV as the access mode, a stated preference survey (Table 1) was also conducted to determine people’s perception of moving to NMV from other modes, which has been depicted in figure 6. As a result, it has been found that 30% of people will mode NMV, whereas walking and car cover only 15% and 12%, respectively.

Figure 7: Willingness to Use NMV (Bicycle and Rickshaw) as Access Mode in NTOD Environment

D. Justification of NTOD for Implementation in Dhaka

After developing the regression model and determining the spatial extent of NTOD, we have a picture of its benefits in the spatial aspect. First, however, we should justify the three key aspects that arise: the built-up area with high population density, the cost-effectiveness of the NTOD idea, and additional traffic jam due to NMV.

Firstly, Dhaka has a high population density with a shortage of new land acquisition. As a result, the land price is rising. However, for implementing NTOD, no new land acquisition is necessary. That is the beauty of this concept. In this case, land readjustment is the most cost-effective and suitable option inherent in NTOD. Additionally, acute phase development plans have already been applied in Taipei in Taiwan to capture land value adequately with four development aspects (Yen et al., 2023). First, this could address the underdeveloped structures with reasonable accessibility. Land readjustment is also essential for rebuilding. Moreover, additional land parcels through land readjustment is an excellent way to determine and influence the urban form (JICA & DTCA, 2015).

Secondly, from the perspective of cost-effectiveness, as no new land development and land acquisition are not necessary, no extra cost will be added for implementing NTOD. Moreover, every conventional TOD requires station parking provision for motorized vehicles. In this case, the access mode will be used as NMV. Typically, in Dhaka, no dedicated rickshaw or bicycle stand is available. Nevertheless, a dedicated bicycle lane will be provided when any transport facility is proposed in the new DAP. So, in this case, additional cost for a bicycle should not be a problem as it will be inherent in any transport facility design. Moreover, NTOD requires spatial and functional reassignment and improvements regarding right-of-way with bicycle usage. Therefore, development is relatively more straightforward and involves fewer investment costs (Lee et al., 2016). In addition, NTOD is more eco-friendly, meaning less fuel consumption, reducing fuel costs. Moreover, its accessibility by NMV (Samimi et al., 2009) has more affordability and congestion reduction (Timpabi et al., 2021). Therefore, the cost due to congestion will be reduced. So, NTOD can be inferred as a more cost-effective planning strategy than any other transport plan in Dhaka (Uddin et al., 2023).
Finally, the rickshaw is already in significant para transit in our transport system. We cannot ignore it. So, we can harness the potential of the rickshaw properly, making an access mode for NTOD. Rickshaw is the eco-friendly mode, and TOD supports this access mode like a bicycle. Dedicated rickshaw lanes and parking stands can manage additional traffic jams generated by rickshaws (Uddin et al., 2019). Moreover, TOD prioritizes less travel distance by automobiles and vehicle occupancy. As the rickshaw covers less travel distance than the car, only proper traffic management near TOD nodes will ease traffic congestion. Additionally, the rickshaw will provide door-to-door service from transit nodes which will work as an additional feeder service (Dey et al., 2018). So, this has more benefits than the odds.

4. CONCLUSIONS

This paper has introduced a new concept for TOD in Dhaka based on the BTOD. Though walking-based trip chains primarily dominate for MRT 6, the contribution of NMV-based trip chains also shows considerable potential. For that, we can go to the new concept of NTOD for Dhaka. However, from the developed regression models for access trips, the cubic model is the most appropriate for determining the spatial extent of TOD. In Dhaka, the catchment area of NTOD can increase the accessibility potentially by spatial extent expansion of about 70% from the conventional TOD. So, it can be inferred that NVM will give more spatial accessibility than walking. As a result, a new window of planning and design strategies will be opened for the planners and policymakers around TOD station area planning considering NMV. Therefore, planners and policymakers should consider these pictures about area planning around stations. If NTOD is introduced, alternative strategies should be implemented for the TOD station development and the adjacent area. NTOD is very efficient in this manner. After rigorous analysis, we recommend NTOD as a future development tool for station area-based planning of the proposed MRT lines in Dhaka. NTOD means making more business and residential places, street amenities, and density accessible by bicycle and rickshaw. The station impact area should be re-established with bicycles and rickshaws as the principal access modes in an NTOD environment. The density criteria could be eased than in a TOD situation. Moreover, the new concept optimizes access to transportation centers by adjusting density distribution rather than total density. Planners and policymakers must consider parking provisions for bicycles and rickshaws to promote NTOD while planning station-wise.

Finally, this research is substantial in that it defined the idea of NTOD and recommended a spatial extension of NTOD for MRT 6 by integrating NMV and public transportation in Dhaka. Future results from a more comprehensive study could be utilized to scientifically quantify the NTOD extent in a particular city to ensure the correct implementation of the NMV facility. For instance, the expansion of cities, the forms of transit, and the sophistication of the network are all significant factors influencing the NTOD spatial extent. For this reason, prospective surveys ought to encompass the qualities mentioned earlier in acquiring a more comprehensive evaluation of the spatial extent.

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Transport Policy (draft)


Effect of Heat Input on the Wire-Arc Additive Manufactured Steel Structures

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ABSTRACT

Wire arc additive manufacturing (WAAM) is one of the less-explored metal 3D printing technologies that hold up a huge potential for large-scale product manufacturing across multiple industries. The low-cost AM uses arc energy as a heat source and metallic wire as a feedstock material. The process is sustainable and supports green manufacturing. However, the major challenge associated with the WAAM is that heat management leads to the development of residual stress causing dimensional inaccuracy and poor surface finish. Therefore, four-layer straight wall structures are fabricated by depositing material layer-upon-layer with nine distinct heat inputs (HI). The prime focus of the work is to study the effect of HI on the dimensional accuracy and the quality of deposited structures. The influence of deposition height on the surface topography is investigated. Furthermore, the effect of HI on the mechanical properties of the WAAM-printed thin wall is examined. The results show that with increase in the number of depositing layers, surface roughness values get increased under the similar process parameter used for the part fabrication. Therefore, it is recommended to re-adjust the process parameter after certain layers of deposition with proper monitoring of the thermal condition in the deposited layers while fabricating medium to large WAAM components. The outcomes from the studies show that increases in the HI while fabricating the WAAM component deteriorates the surface quality of the deposited layer and are responsible for reducing the mechanical properties of the WAAM-printed component.

1. INTRODUCTION

Wire and arc additive manufacturing (WAAM) is a revolutionary process classified under directed energy deposition (DED) that utilizes the combination of metallic wire as a feeding material and arc heat energy as a heat source to fabricate structures by depositing materials layer upon layer (Kumar et al., 2021). The welding-based additive manufacturing (AM) has exceptional application potential in marine ships, aerospace, automobiles, petrochemical, nuclear power, and many other industries that serve the dual purposes of manufacturing and remanufacturing the components (Hideaki et al., 2020). The manufacturing method offers several advantages over traditional manufacturing such as high flexibility, high energy efficient process, integral forming, sustainable manufacturing, low capital cost, low buy-to-fly (BTF) ratio, and short manufacturing lead time (Gisario et al., 2019). The repeated heat cycle during material deposition and the discrete-stacking principle is liable to generate thermal stresses and metallurgical defects in the parts fabricated via WAAM (Zeng et al., 2021). The surface quality and dimensional accuracy of the structure built strongly depend on the fabrication process parameters that ultimately determine the molten pool size, temperature, and molten metal viscosity. These WAAM process parameters, in combination with heat dissipation conditions, determine the rate of solidification, grain size, and orientation that impact the morphological evolution and mechanical strength of the built structure (Filippov et al., 2021). Besides several limitations, the low-cost WAAM manufacturing technique remains most suited for printing large-scale components because of better material utilization and a high material deposition rate compared to other metal additive manufacturing. In the area of improving the quality of WAAM fabricated component studies have been carried out by researchers in different domains. Wang et al. investigated the influence of heat input

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on the microstructure and mechanical properties of the WAAM-deposited Al-Cu-Sn alloy. The authors observed an increase in the size and number of pores within the deposited alloy leading to reduce its mechanical strength (Wang et al., 2020). Another researcher studied the impact of preheating the base plate and cooling the substrate plate on the geometry of the deposited weld bead using the WAAM process (Gudur et al., 2021). Zhou et al. performed several experiments to optimize the process parameter to reduce heat input to the WAAM process and improved the surface quality of the fabricated part (Zhou et al., 2020). To minimize problems of residual stress in the WAAM-built part researchers used the roll pressure technique while fabricating parts that not only refine the grain structure but also reduce the geometric distortion and control the residual stress (Hönigse et al., 2018). Furthermore, the effect of temperature on the mechanical properties of the fabricated aluminum alloy has been investigated, and results show an improvement in the micro-hardness and tensile properties of the built specimen when the built specimen undergoes the solution treatment and natural aging (Zewu et al., 2018). Guo et al. investigated the effect of heat treatment on the microstructure and mechanical properties of the WAAM fabricated wall structures. The application of heat treatment improves tensile strength and ductility and reduces the mechanical anisotropy along the vertical and horizontal direction of the fabricated wall (Guo et al., 2022). On the other side, the researcher worked to rectify one of the major problems of surface waviness restricting the economical use of the as-deposited WAAM component. The concept of side rolling of the deposited layers at room temperature while fabricating the structure has been introduced which lowered the surface waviness and also improved the strength due to work hardening (Dirisu et al., 2020). Xiong et al. studied the effect of process parameters on the quality of deposited structure (Xiong et al., 2018). They observed that by maintaining a constant ratio of wire feed speed and travel speed, the surface roughness increased with the increase of wire feed rate. Thus, the WFR was found to be the major influential parameter deciding the forming appearance of thin wall WAAM components.

Critical analysis of the literature sources is mostly devoted to the investigation of process parameters in correlation to their micro-structural changes and mechanical behaviour of the WAAM fabricated part. Therefore, as per the author's best knowledge study based on the effect of heat input on the surface topography, surface quality and mechanical properties of the WAAM printed components have been the least explored research areas in this domain. Therefore, the objective of the work is to fabricate four-layer straight wall structures at nine different heat inputs. The extracted sample was further used to study the impact of heat input on the surface quality of the printed wall along the deposition direction by calculating average surface roughness values using the roughness tester and surface waviness of the deposited layers using the non-contact optical profilometer. The study continued with investigating the impact of heat input on the mechanical properties of the built wall structures and examined different phases and compound formations for the samples printed at different heat inputs.

### 2. MATERIALS AND METHOD

#### A. Experimental Procedure

The experimental setup utilizes GMAW welding equipment integrated with the MINI CNC 1530 machine. The material deposition rate and the heat source were controlled by the welding machine while the deposition path and its speed were controlled by the CNC machine. The experimental setup of the GMAW-based WAAM system is illustrated in Figure 1.

![Figure 1: The experimental setup for GMAW-based WAAM technologies](image)

#### B. Materials Selection

The Stainless steel MIG wire (SS316) of diameter 0.8 mm is used as the feedstock material and the AISI1018 steel plate as the substrate for material deposition. The chemical composition of the filler wire and substrate plate is presented in Table 1. The WAAM process is used to fabricate nine thin straight wall structures of 60mm in length through successive deposition of four layers of metal by varying the heat input in each case.

<table>
<thead>
<tr>
<th>Elements</th>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>Ni</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate (%WL)</td>
<td>0.17</td>
<td>0.01</td>
<td>0.8</td>
<td>0.32</td>
<td>0.01</td>
<td>0.004</td>
<td>Bal.</td>
</tr>
<tr>
<td>Wire (%WL)</td>
<td>0.07</td>
<td>17.0</td>
<td>2.3</td>
<td>0.32</td>
<td>0.04</td>
<td>8.91</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

#### C. Heat Input and Process Parameters

The WAAM process parameters used during the additive process are listed in Table 2. The stand of distance (SOD) and interlayer dwell time for layers’ deposition has been maintained at 10 mm and 60 seconds respectively. The protective gas CO₂ (99.99%) has been used as the shielding medium with a flow rate of 20 L/min maintained during part printing. It provides stability in the process, improvement in the surface finishing quality, and a reduction of the splatters during the process. Furthermore, to investigate the surface topography of the WAAM fabricated surfaces, a square shape structure of 21 layers and a circular shape structure of 15 layers were fabricated using ER70S-6 MIG wire of 0.8 mm diameter considering the optimal process parameters from the previously...
published additive process, the thermal input is calculated in each set experiment using Equation (1) (Pépé et al., 2011)

\[ H.I \ (J/mm) = \eta \times \frac{U \times I \times 60}{TS (mm/min)} \]  

(1)

Where HI (J/mm) is the liner heat input of the arc deposition process, \( \eta \) is the thermal efficiency of the GMAW-based WAAM process set to 0.8, U and I are the arc voltage and welding current and TS is the travel speed or deposition speed in (mm/min). It can be seen from Equation 1 that changing the process parameters such as current, voltage, and welding speed can alter the heat input of the fabricated specimen. The influence of heat input on the geometry of the printed wall has been analyzed by changing the arc voltage and current during the WAAM layer deposition process. The dimension of the deposited wall i.e. bead height and bead width has been measured using a digital Vernier Caliper and the average value has been obtained for further study. The average wall height and wall thickness as the process responses have been obtained for each set of the fabricated wall. The final printed four-layered wall by melting a wire using arc energy based on the principle of wire arc additive manufacturing process has been shown in Figure 2. The WAAM process comes with the advantage of a much higher material deposition rate with respect to other metallic additive manufacturing processes (Sydow et al., 2022). In addition to this, a higher working speed allows working with a higher workload and a significantly lesser cost of manufacturing than other AM methods of such category.

### Table 2

<table>
<thead>
<tr>
<th>Samples</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>HI (J/mm)</th>
<th>Avg. wall Height (mm)</th>
<th>Avg. wall Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>14</td>
<td>80</td>
<td>162.90</td>
<td>8.59</td>
<td>9.34</td>
</tr>
<tr>
<td>2#</td>
<td>16</td>
<td>85</td>
<td>197.81</td>
<td>8.45</td>
<td>8.83</td>
</tr>
<tr>
<td>3#</td>
<td>18</td>
<td>90</td>
<td>235.64</td>
<td>8.51</td>
<td>8.97</td>
</tr>
<tr>
<td>4#</td>
<td>20</td>
<td>95</td>
<td>276.36</td>
<td>8.79</td>
<td>9.25</td>
</tr>
<tr>
<td>5#</td>
<td>22</td>
<td>100</td>
<td>320.00</td>
<td>8.87</td>
<td>9.58</td>
</tr>
<tr>
<td>6#</td>
<td>24</td>
<td>105</td>
<td>366.54</td>
<td>8.95</td>
<td>9.53</td>
</tr>
<tr>
<td>7#</td>
<td>26</td>
<td>110</td>
<td>416.00</td>
<td>9.18</td>
<td>10.01</td>
</tr>
<tr>
<td>8#</td>
<td>28</td>
<td>115</td>
<td>468.36</td>
<td>9.53</td>
<td>10.15</td>
</tr>
<tr>
<td>9#</td>
<td>30</td>
<td>120</td>
<td>523.63</td>
<td>9.61</td>
<td>11.37</td>
</tr>
</tbody>
</table>

Deposition Speed (mm/min): 330

The obtained process response (wall height and width) has been used to study the influence of thermal input on the printed wall geometry. Further, the effect of heat input on the surface quality of the wall has been studied. The surface waviness along the building direction of the printed wall and surface roughness of the final deposited layers has been obtained by using a non-contact optical profilometer and contact-type roughness tester respectively. The fabricated four-layer wall has been sectioned accordingly to investigate the effect of heat input (HI) on the mechanical properties of the deposited wall.

### Figure 2: Fabricated WAAM specimens with different Heat Inputs

### 3. RESULTS AND DISCUSSION

#### A. Effect of Heat Input on Forming

The printed wall geometry is quantified in terms of average wall height and average wall thickness. The measurement of the height and width of the deposited layered structure is taken by the digital vernier caliper (Model: Mitutoyo 500-196). The effect of heat input on the fabricated wall geometry has been plotted and presented in Figure 3. The results show that the average wall height of the built wall gradually increases with the increase of the heat input to the fabrication process. A similar trend is also followed for the average thickness of the printed four-layer wall structure. The higher thermal input to the process means sufficient heat that can create a better shaped-molten pool layer-upon-layer and provides an improved stabilization effect on the molten pool (Zeng et al., 2021). However, too high heat input results in a higher volume of the molten pool that is expected to spread on the deposited layer deteriorating the geometrical dimension and accuracy. This can be observed from the percentage increases in the average height of sample 9# that gets slightly decreased when compared to sample 8#. On the other hand, to this, lower heat input to the process provides insufficient heat to melt the electrode material in time during layer deposition, and therefore the degree of change in the shape of the molten pool becomes relatively severe. And, the less volume of the melted material during layer deposition reduces the dimension of the printed wall and material deposition efficiency of the WAAM process. The study observed that too high or too low thermal input to the WAAM fabricated specimen is detrimental. Therefore, it is very much critical to adjust and properly select the heat input during the WAAM process as it not only changes the geometry of the printed wall but the existing cooling rate also affects the microstructures and the residual stress within the deposited layers (Jafari et al., 2021).
B. Effect of Heat Input on Surface Roughness

The quality of the fabricated layered structure is measured in terms of average surface roughness along the deposition direction over the top surface of the final deposited layer. The surface waviness of the built structure along the build direction is analyzed using a non-contact 3D optical profilometer (Model: Zygo, Ametek Newview-9000). However, portable and contact-type surface roughness testers (Model: Mitutoyo SJ-210) were used to obtain the average surface roughness value (Ra) on the top deposited layer of the built structure. The roughness measurement was conducted according to the ISO 4287 standard (Iso, E.N., 1997). The samples before the observation were cleaned using acetone to remove dirt particles. The sampling length and a cut-off length for the contact type roughness tester were taken as 2.4 mm and 0.8 mm respectively. The roughness values were measured at five different locations on the top surface of the final deposited layer for each specimen and the arithmetic means were taken for further analysis. The heat input was found to have a high degree of influence on the surface quality of the fabricated WAAM specimen. There has been a direct dependency of heat input on the surface roughness of the printed wall. Figure 4 shows the bar graph with the error bar scale for the obtained average surface roughness (Ra) on the top surface of the nine WAAM printed specimens against the different heat inputs to their manufacturing process.

The increase in heat input deteriorates the surface quality and increases the surface roughness value on the top surface of the fabricated four-layered wall. It has been observed that the application of high heat input to the WAAM process leads to high heat accumulation and overheating of the deposited material which reduces the surface tension making the molten pool unstable and resulting in a sometimes overflow of the molten pool, arc instability, spattering and the impact of arc force leads to a low quality of forming. The surface roughness was found to be reduced with lower heat input but this limited the entire purpose of using WAAM as a low-cost metal additive process. Therefore, to harness the full benefit of WAAM technology, a compromise between the process productivity, surface quality of the printed parts, and mechanical properties needed to be made. Figure 5 shows the 3D surface profile and waviness profile of the printed wall along the building direction of WAAM fabricated specimens at four different heat inputs.

The scan area for the non-contact type optical profilometer is taken as 5.65×3.14 mm. Surface waviness is one of the important parameters to define the quality of WAAM-deposited layers to fabricate different structures. From the literature, it is defined as the maximum peak-to-valley distance measured from the surface profile of the deposited wall. Therefore, the arithmetic mean of the maximum distance between peaks to the valley heights of the deposited layers along the wall-building direction has been obtained using the ImageJ software to quantify the surface waviness of the printed WAAM structure. The values obtained as 1050μm, 910μm, 925μm, and 1169μm for sample 1#, sample 4#, sample 5#, and sample 9#, respectively.

Surface waviness in the WAAM printed walls can also be interpreted as the difference between total wall width (TWW) and effective wall width (EWW). The TWW is the wall thickness directly after the layer deposition while the EWW is the maximum wall width reached after the post-finishing operation of the WAAM printed structure. These observations were used to analyze the effect of different levels of heat input on the built straightness of the WAAM fabricated structure. The build straightness for the multilayer components defines as the deposition of material layer upon layer along the straight-line direction which would be beneficial as the deposited layers closer to
the straight-line result in the least deviation from the wall geometry and therefore require the least post-machining process to correct it. The study found a minimal surface waviness for sample 4# fabricated at 276.36 J/mm. However, the sample fabricated at lower and very high thermal input experienced a greater average value of surface waviness i.e. peak to valley height of the deposited wall along the building direction. The increase in the heat input is responsible for heat accumulation within the printed components that have detrimental effects such as increase in the size of the molten pool and widening of the deposited layer, surface waviness, non-homogenous material along the building direction, and even collapse of possible structure at extremely high heat input. Therefore, well-established management of thermal input can only improve additive manufacturing (AM) part quality and accuracy.

![Sample Images](image1.jpg) ![Sample Images](image2.jpg) ![Sample Images](image3.jpg) ![Sample Images](image4.jpg)

**Figure 5:** 3D profile image of wall surface and waviness profile of the WAAM-built components at different Heat Inputs

### C. Effect of Heat Input on Mechanical Properties

The samples from each printed wall were sectioned and prepared mold using a hot mounting press machine for easy handling of samples. The extracted samples were further polished to remove mild scratches and uneven surfaces. The Vickers micro-hardness test using a repulsive hardness tester (Model: HM220, Mitutoyo Japan) is carried out on the nine extracted samples along the building direction. A load of 0.5 Kgf and a dwell time of 10 seconds were taken as the testing parameter. The hardness tester
uses a pyramidal shape diamond indenter and Quantinet software integrated with the machine for image analyzing and estimating hardness values. The bar graph plotted for the mean hardness value of each tested sample against the heat input to the fabrication process is displayed in Figure 6. The observation shows that the mean hardness value along the building direction decreases with an increase in the heat input to the fabrication process. The high heat input is responsible for increasing the size of dendrite arms spacing due to a lower solidification rate while depositing material layer upon layer thus deteriorating the mechanical properties (Malin, et al., 2020). The slower cooling rate preferentially forms the columnar grain structure in the printed wall also responsible for decreasing the trend of micro-hardness with the increase in heat input. Additionally, it is evident that the interface zones of the printed wall have a higher micro-hardness value compared to it deposited material. Therefore, a suitable inter-pass cooling strategy while depositing material layer by layer can minimize the heat accumulation of the previously deposited material and brings up an almost equivalent solidification rate for each deposited layer. That will result in the least variation in the microstructures along the building direction of the printed. The previous study also found a negative impact of higher heat input on the surface roughness and mechanical properties of the material (Filippov et al., 2021; Chengxun, et al., 2021; Nor Ana, et al., 2021). The use of lower heat input for depositing material layer upon layer along with an application of an inter-layer cooling technique found to be an effective method for grain refinement and reducing mechanical anisotropy (Chengxun, et al., 2021).

Figure 6: Average hardness value of the WAAM printed wall at different heat inputs

D. Phase Analysis at Different Heat Inputs
X-ray diffraction (XRD) phase analysis has been performed on the selected printed wall samples to investigate and distinguish different phases and compound formation at different levels of heat input. For this analysis, the samples were fabricated at minimum and maximum heat inputs e.g. sample 1# and sample 9#. Besides, two samples were also built at the moderate heat input e.g. sample 4# and sample 5# for the analysis. The samples were tested under the high-resolution (HR) XRD machine (Model- SmartLab studio II) with a radiation source of copper K-α at 40 kV. The diffraction angle (2ϴ) of 20 to 120, step size of 0.02, and a scan speed of 1 degree/min are considered as the testing parameters for the generation of XRD peaks. Figure 7 illustrates different peaks and compound formations for samples 1#, 4#, 5#, and 9# printed at different heat levels. The XRD spectra show the presence of intense bcc peaks of residual ferrite (011), (111) (002), (112) for sample 1# along with iron carbides and other solid solution and precipitate responsible for the higher hardness of the tested sample confirming the result of higher hardness value at lower heat input observed under the Vickers micro-hardness test (Garcia-Cabezon et al., 2022). The crystalline phases and compounds having a less intensity peak with a volume fraction lesser than five percent were not been detected in the XRD spectrum of the tested specimen. Furthermore, the sample fabricated at higher heat input shows intense peaks of austenite (111), (002), and (022) in the XRD spectra responsible for the lesser hardness and higher ductility of the fabricated sample (Yadollahi et al., 2017). The peaks also indicate the presence of different oxides of chromium and nickel for sample 9# fabricated at a higher heat input that may be responsible for deteriorating wall quality and impart defects like porosity, and blowholes within the deposited wall built at high thermal input (Keichiro et al., 2009; Miao-Xia et al., 2019). Other than these, identical peaks can be observed for sample 4# and sample 5# printed at moderate heat input with the presence of precipitate and compounds such as chromium-nickel, iron phosphide, manganese nickel, and copper silicon apart from ferrite and austenite phases.
E. Surface Topography

The WAAM process when compared to other AM has the advantage of higher material deposition rate that can be reached up to 100% with the right selection of process parameters. However, the surface quality of the deposited parts is always a point of concern to meet the industrial requirement leading to subsequent post-processing of the fabricated parts (Wu et al., 2017). For investigating the surface roughness of two different shapes of WAAM-built structures, 21-layer square shape (A) and 15-layer circular shape (B) components were fabricated using ER70S-6 MIG wire considering the optimal process parameter from the previously published literature (Kumar et al., 2021). Figure 8 displays the three-dimensional (3D) surface profile of the top and bottom regions of the WAAM fabricated component (A) and (B). The 3D non-contact optical profilometer has been used to scan the surface topography of the WAAM-printed walls. The two most important factors used for the evolution of the surface texture of the deposited wall are: $S_a$ (define the arithmetic mean height of the surface) and $S_q$ (define the root mean square height of the surface). The higher value of these two factors for any deposited wall is expected to have a higher roughness value and the surface will be difficult for post-machining due to a rise in its frictional coefficient (Sedláček et al., 2009). According to the results, the circular shape structure (Component-B) samples possess a lower value of surface roughness with $S_a=101.542 \ \mu m$ and $S_q=113.962 \ \mu m$ along the bottom region in comparison to the square shape structure (component-A) with $S_a=104.325 \ \mu m$ and $S_q=120.597 \ \mu m$. The scanned areas for the surface profile were chosen away from the bottom and topmost layer of the printed parts where the dimension of the deposited layer is mostly unstable because of the initiation and extinguishing of the arc. The observation from the surface profile along the top and bottom regions of both the components shows a higher roughness value in the top regions of the fabricated component. Thus, the uneven surface appearance and the stair-step effect can be observed in both the printed parts along the building direction with an increase in the number of deposited layers. The higher value of surface waviness generates higher surface roughness on the deposited wall. The surface roughness of the WAAM printed parts depends upon the selected process parameters such as shielding gas, deposition speed, wire feed rate, filler wire diameter, heat input (arc voltage and current supply), and solidification time (Zhijun et al., 2021). For the fabrication of cylindrical shape component B, the welding torch completes one cycle of metal deposition in lesser time around the circular path of diameter ($d=22 \ mm$) in comparison to square shape wall of dimension ($l=30 \ mm$, $b=30 \ mm$). Thus, component B gets less time for solidification and so less heat gets accumulated on the deposited layers. This causes reducing
the overflow of the molten pool during the deposition of the next layer which could be a reason for decreases in the surface roughness value in comparison to component A. The WAAM fabricated component-A undergoes post-machining and the uneven surface was machined to reduce the large waviness in the deposited layer. The 2D and 3D surface roughness profiles of the post-machined printed component-A have been shown in Figure 9. The result shows an overall reduction in surface roughness value of the WAAM fabricated component-A with $S_a = 6.051 \mu m$ along the horizontal direction and $S_a = 9.129 \mu m$ along the vertical direction of the deposited layers.

Figure 8: 3D Surface roughness profile of the WAAM fabricated components A and B

Figure 9: 2D and 3D Surface roughness profile of the post-machined WAAM fabricated Component-A
4. CONCLUSIONS

The critical analysis of surface quality in terms of surface roughness parameters and the effect of thermal input on the surface roughness of the deposited layer, part dimension in terms of wall height and thickness along with mechanical properties of the deposited four-layer wall structure have been concluded as follows.

- Too high or too low thermal input to the WAAM-built specimen is detrimental and therefore fabrication method is required to optimize the heat input to achieve high quality built structure consuming minimal energy with high material deposition efficiency.

- The increased heat input deteriorates the surface quality and surface roughness value on the top surface of the fabricated four-layered wall structure. Also, the surface waviness (peak-to-valley height) largely increased at very high thermal input to the WAAM printed components.

- There has been a negative impact of higher heat input on the mechanical properties of the built structures. The use of optimal heat input for depositing material layer upon layer along with an application of an inter-layer cooling technique concluded to be an effective method for grain refinement and reducing mechanical anisotropy.

- The XRD phase analysis confirms the presence of the intense peak of ferrite along with other carbides and precipitates responsible to impart higher hardness to the WAAM-built structure at lower heat input. Thus support the observation from the micro-hardness testing.

- The surface roughness values along the building direction increase with the number of deposited layers for both the WAAM fabricated component-A (square shape structure) and B (circular shape structure). The cylindrical shape structure was found to have a lesser roughness value when compared to the square-shaped structure.

The study investigates the influence of equivalent heat inputs on the formability, surface quality, and mechanical properties of the WAAM fabricated steel structures. However, an in-depth study based on the impact of heat input on the grain morphology, and tribological performance along different orientations needs further investigation. Also, different cooling strategies to mitigate the excessive heat accumulation and anisotropic behaviour of the WAAM-built structures are some other future scope of the research work.

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A Zero-Equation Model for External Aerodynamics

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ABSTRACT

The zero-equation model (ZEM) has been generalized for aerodynamic applications by eliminating the thickness of boundary-layer (BL) dependency to construct the stress length parameter \( I_{12} \). The SED (Structural Ensemble Dynamics) postulate evaluates the \( I_{12} \) using the order function based on universal multi-layer structures for wall turbulence. The SED concept is further employed to optimize the profiles of the turbulent kinetic energy and dissipation rate with turbulent BL flows. Results demonstrate that the multi-layer ZEM receives a remarkable achievement in the prediction of wall-bounded turbulence and thus, prevails over the drawbacks encountered in most algebraic turbulence models.

NOMENCLATURE

AOA angle of attack
BL boundary layer
\( C \) airfoil cord length
DI dilation invariance
DS dilation symmetry
\( K \) kinetic energy of turbulence
\( I_{12} \) stress length
\( P \) pressure
\( R_b \) factor of stress-intensity
\( Re \) Reynolds number
\( R_T \) eddy-to-laminar viscosity ratio
\( S \) mean strain-rate tensor
SED structural ensemble dynamics
SST shear stress transport
\( u_i \) velocity vector

\( u_T \) wall-friction velocity
\( Y \) distance to wall
\( y^+ \) wall distance parameter; \( u_c y/v \)
ZEM zero-equation model
\( \delta \) BL thickness
\( \epsilon \) rate of turbulence dissipation
\( \kappa \) von-Karman constant
\( \mu, \mu_T \) laminar & eddy viscosities
\( \nu \) laminar kinematic viscosity
\( \rho \) density

Subscript:
\( i, j \) variable quantities
\( \infty \) free-stream condition

1. INTRODUCTION

To develop a zero-equation model (ZEM), the correlation-based turbulence modelling with a dimensional argument may induce lots of functions and coefficients which lack physical interpretations (Wilcox, 2006). The devised turbulence model with this inconsistent aspect typically inherits unexpected complications to accurately predict the flow with practical features. However, the physical understanding of the universal structure related to wall turbulence can provide a compelling route to format a ZEM in conjunction with “Reynolds-averaged Navier-Stokes (RANS)” equations. The current research applies a well-established physics of wall turbulence to formulate a plausible ZEM, which is unfortunately beyond the capacity of the mixing length hypothesis of Prandtl (1925), von Karman lag-law theory (Segalini, 2013) and Townsend similarity argument (1976).

The “SED theory” of She et al. (2010, 2017, and 2009) aims at using the turbulence statistical symmetry to make a quantitative description of the wall-bounded turbulence feasible. The dilation symmetry (DS) deserves an outstanding significance due to a universal wall constraint...
on turbulence eddies, since the DS determines the solutions to RANS equations through the relevant order parameter/function (whose role of symmetry remains prevalent to wall flows), describing ensemble properties emerged from turbulence fluctuations which restore a DS (layer by layer) and the order-function scaling can quantify the symmetry property (She et al., 2017). More precisely, the mean velocity is altered by inherent turbulence fluctuations in association with the Reynolds stress leading to symmetry breaking; however, a length order function can handle this interaction (effect) with its dilatation-invariance (DI) scaling, showing a perceptible nature from one layer to another. Under a “generalized Lie-group” DI, the SED concept employs a multi-layer formulation of the order function (key to quantifying turbulence) to speculate the stress length $l_{12}$ with a fully-developed turbulent BL flow. The analytic profile is ended up with “four-layer structures”, consisting of a viscous sublayer, buffer layer, bulk flow region (retaining log-layer) and core layer. Apparently, variances among different layers of a physical flow domain can be represented by the variations (layer-to-layer transition sharpness and scaling) in multi-layer parameters. A ZEM has been recently developed using the SED concept (wall-turbulence with distinct multi-layer physics) (Rahman et al. 2021), where the kinematic eddy-viscosity is evaluated as $V_T = I_{12}^2 S$ with the strain-rate invariant $S$. The “Bradshaw stress-intensity parameter” $R_b$ (Bradshaw, 1967) which is a function of an eddy-to-laminar viscosity ratio $R_T$ has been used to model the turbulent kinetic energy $k$ and dissipation-rate $\varepsilon$. The resulting ZEM provides reasonable predictions for a fully-developed channel flow. However, the ZEM needs to evaluate boundary layer (BL) thickness parameter $\delta$ in forming the stress length $l_{12}$, which is difficult to be included in three-dimensional numerical algorithms. More specifically, aerodynamic applications usually integrate the BL influence of the wall curvature, although the BL edge is not well-defined, reflecting numerical confusion to accurately determine $\delta$. This deficiency has been eliminated from the stress length $l_{12}$ by replacing the bulk flow region and core layer with an additional transition layer (log-layer) and the celebrated matching layer. Improved $k-\varepsilon$ analytic profiles are obtained as a combination of the Bradshaw parameter and another optimized $k$ profile for a fully-developed BL flow using the SED hypothesis. A cursory examination approves that the multi-layer ZEM dominates over the past developed algebraic turbulence models (Prandtl, 1925; Segalini et al., 2013; Townsend, 1976; and Wilcox, 2006).

2. GOVERNING EQUATIONS

In collaboration with the RANS turbulence modelling, the turbulent eddy-viscosity $\mu_T$ has been evaluated by the stress length scale with regards to the “SED theory”. The RANS equations describe the physics of a continuum medium using the mean conservations of mass, momentum and energy. The differential formulations in tensor form read:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = - \frac{\partial P}{\partial x_i} + \frac{\partial \sigma_{ij}}{\partial x_j} \tag{2}$$

$$\frac{\partial}{\partial t} \left( \rho e + \frac{\rho u_i^2}{2} \right) + \frac{\partial \left[ \rho u_i \left( h + \frac{u_i^2}{2} \right) \right]}{\partial x_j} = \frac{\partial u_i \sigma_{ij}}{\partial x_j} - \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu + \mu_T}{\Pr} \right) \frac{\partial T}{\partial x_j} \right] \tag{3}$$

where $\rho$ the fluid density, $P$ the static pressure, $u_i$ the $i$th component of velocity and $x$, the Cartesian coordinates, $e$ the specific internal energy, and $h = e + \rho \frac{u_i^2}{2}$ represents the specific enthalpy. The working fluid is air; the laminar Prandtl number $Pr = 0.7$ and turbulent Prandtl number $Pr_T$ is set to 0.9. The laminar viscosity $\mu$ is calculated from Sutherland’s formula. The “equation of state” is $p = \rho RT$ for a calorically perfect fluid, where $R$ the perfect gas constant and $T$ the absolute temperature. Additionally, $e = C_v T$ and $h = C_p T$, where $C_v$ and $C_p$ are the specific heat coefficients at constant volume and pressure, respectively.

The “Boussinesq approximation” can be used to relate the total stresses $\sigma_{ij}$ with the “mean strain-rate tensor” $S_{ij}$ as:

$$\sigma_{ij} = 2 \left( \mu + \mu_T \right) \left( S_{ij} - \frac{1}{3} S_{kk} \delta_{ij} \right), \tag{4}$$

$$S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

where $\delta_{ij}$ implies Kronecker’s delta function with $\delta_{ij} = 1$ for $i = j$ and $\delta_{ij} = 0$ for $i \neq j$. The “SED theory” applies the stress length function $l_{12}$ to define $\mu_T$ as:

$$\mu_T = \rho V_T = \rho l_{12}^2 S, \tag{5}$$

where $S \sqrt{2S_{ij} S_{ji}}$ is the mean strain-rate invariant.

The “SED theory” states that a proper set of order functions can represent the wall turbulence, retaining complex systems with multi-layer structures (She et al. 2010). A quantitative analysis of the “generalized Lie-group” DI can be applied to deduce the characteristic order function (in a framework of
multi-products) as the wall is present. The generic form of the order function $\phi$ with complex multi-layer structures can be given as (She et al., 2017):

$$\phi = c_0 \left( \frac{y}{a_0} \right)^{\alpha/b_0} \prod_{i=1}^{n} \left[ 1 + \left( \frac{y}{a_i} \right)^{b_i} \right]^{\alpha/b_i}$$  \hspace{1cm} (6)$$

where $\phi$ is parameterized with a variable $y$; adjustable constants are (a, b & c) with the number of products, $n$. In principle, multiple transitions from one layer to another occur due to the spatial variation of $\phi$. Naturally, the stress length $l_{12}$ associates multi-layer features in a fully-developed turbulent BL, as supported by the SED hypothesis, which provides the formulation of $l_{12}$ for a fully-developed channel flow as (She et al., 2017):

$$l_{12}^* = l_0 \left( \frac{y^*}{9.7} \right)^{3/2} \left[ 1 + \left( \frac{y^*}{9.7} \right)^{4}\right]^{1/8} \left[ 1 + \left( \frac{y^*}{41} \right) \right]^{1/4}$$

$$1 - r^4 \frac{4(1-r)}{4(1-r)} + \left[ \frac{0.27}{r} \right]^{2/3}$$  \hspace{1cm} (7)$$

where the non-dimensional wall-distance $y^* = y u_t / \nu$ with the “wall-friction velocity” $u_t = \sqrt{\nu S} / \mu$ and laminar kinematic viscosity $\nu = \mu / \rho$. Note that $u_t$ can be regarded as a well-defined parameter as long as $S_w > 0$.

Additionally, $r = 1 - y^*/\delta = 1 - y^*/R_{\lambda}$ implies the distance from the channel center-line, where the channel half-width $\delta$ and friction Reynolds number $R_{\lambda} = \delta u_t / \nu$ . Equation (7) describes canonical four-layer structures (as mentioned earlier) of wall turbulence with a fully-developed BL channel flow. The extension of each layer is identified empirically by its layer thickness. They are the viscous sublayer at $y_{sub} = 9.7$, buffer layer at $y_{buf} = 41$, core layer with a core layer thickness of $r_{core} = 0.27$ and bulk-flow region. A detailed description of the various layers can be found in Reference (Rahman et al., 2021). Note that the geometry-dependent bulk-flow structure $1 - r^4$ avoids the existence of the overlap region.

It is worth mentioning that $y^* >> y_{buf}$, the celebrated linear law $l_{12} \approx \kappa y^*$ (where von-Karman constant $\kappa = 0.45$ from the “SED theory”), represents a “matching function” presumably between BL “inner and outer regions” with $l_0 \approx 9.7^2 \kappa/41 \approx 1.0$. The outer region can be described using the parameters $r$ and $\delta$, defined as the position of 0.99$U_\infty$ at the BL edge with the free-stream velocity $U_\infty$.

However, the evaluation of $\delta$ creates a practical problem in the numerical solution to RANS equations. Specifically, two occurrences complicate any attempt in devising a proper algorithm to find the BL edge: firstly, the existence of non-uniform inviscid flow regimes, where the flow changes in the direction normal to the boundary; secondly, the appearance of spurious numerical oscillations in the flow domain. To avoid these issues, Equation (7) has been generalized for external aerodynamic applications in the current study as:

$$l_{12}^* = l_0 \left( \frac{y^*}{9.7} \right)^{3/2} \left[ 1 + \left( \frac{y^*}{9.7} \right)^{4}\right]^{1/8} \left[ 1 + \left( \frac{y^*}{41} \right) \right]^{1/4} + f_b \kappa y^*$$

where $f_b$ signifies a near-wall damping function, defined later. The modified Equation (8) identifies three layers separated at respective distances $y_{in} = 9.7$, 41 and 130, accompanied by the celebrated mixing layer. Apparently, the “SED theory” involves a set of base functions that can describe a series of successive transitions, modeling the entire profile for the whole flow domain. A multi-layer model to describe the k profile in a fully-developed BL flow can be constructed using the “SED theory” as:

$$k^* = 0.131 y^2 \left[ 1 + \left( \frac{y^*}{3} \right)^{2/3} \right]^{1/4} \left[ 1 + \left( \frac{y^*}{8} \right) \right]^{1/6}$$

$$\left[ 1 + \left( \frac{y^*}{20} \right)^{6} \right]^{1/10} \left[ 1 + \left( \frac{y^*}{40} \right) \right]^{1/20}$$  \hspace{1cm} (9)$$

Equation 9 is slightly modified from Reference (Fang & Xu, 2022) to approximate the viscous, buffer and log layers with reasonable accuracy; however, the wake-deficit layer is over-estimated, as will be seen afterward. On the other hand, “Bradshaw’s parameter” $R_{\delta} = -\nu/k \approx \sqrt{C_{\mu}}$ (Bradshaw, 1967) (with the main shear-stress $-\nu\kappa$ and $C_{\mu} = 0.09$) can be used to predict the k profile for wall-bounded flows. Using the SED interpolation scheme [Eq. (6)], the “stress intensity variable” $R_{\delta}$ (parameterized with $R_{\delta} = \mu / \mu$) can be obtained for a fully-developed turbulent BL flow as (Rahman, 2022; and 2023):

$$R_{\delta} = \frac{C_{R_{\delta}}^{0.4}}{(1.0 + R_{\delta})^{0.16} (1.0 + C_{\mu} R_{\delta}^{0.12}$$

where $C_{\mu} = C_{\mu}^{0.9}$, $C_{\mu} = C_{\mu}/5.0$. As $R_{\delta} \rightarrow \infty$, $R_{\delta} \approx C_{\mu}/C_{\mu}^{0.24} \approx \sqrt{C_{\mu}}$. Note that $R_{\delta}$ is extended for
wall-bounded flows from free shear flows, resolving the “near-wall turbulence”. The structure parameter $R_b$ can be employed to calculate $k$ profile in a BL flow as:

$$k_b = \frac{v_t^2S}{R_b + C_k}$$

(11)

where $v_t = \mu \sqrt{\rho}$ the kinematic eddy-viscosity and the near-wall singularity can be avoided with $C_k = 0.001$. Equations (9) and (11) can be interpolated to better replicate the $k$ profile over the whole flow domain. Therefore, $k$ and $\varepsilon$ (dissipation-rate) profiles are evaluated as:

$$k = \frac{k_b^2 + 2k_b}{3}, \quad \varepsilon = R_b k S$$

(12)

Equation (12) represents an empirical hybrid modeling of the $k$ profile. The associated function $f_b$ in Equation (7) is modeled as:

$$f_b = R_b \tanh \left[ \left( \frac{R_b}{70} \right)^2 \right]$$

(13)

The damping function $f_b$ is influential in the proximity of the wall (inside the BL) and promotes the formation of the wake-deficit layer (bulk-flow structure and core layer) outside the BL.

3. NUMERICAL SIMULATIONS

The fully-developed turbulent channel flow, flat-plate BL flow and transonic flow past an RAE2822 airfoil are probably the suitable test cases to validate the performance of the ZEM. The flow equations are numerically solved using an in-house computational code, encompassing a pseudo-compressibility (PC) scheme with a “cell-centred finite-volume” formulation (Rahman and Siikonen, 2001, 2002 & 2008; Rahman 2021 and Rahman et al. 1997). The cell-face convective flux is evaluated using a “fully second-order” upwinding together with Roe’s damping (Rahman, 2021 and Rahman et al. 1997). A DDADI (“diagonally dominant alternating direction implicit”) time integration scheme has been applied to the discretized equations for the iterative solution. A multi-grid method has been employed to stabilize the solver convergence. Refs. (Rahman and Siikonen, 2001, 2002 & 2008; Rahman 2021 and Rahman et al. 1997) detail the salient features of coding a PC scheme. Results from the standard “shear-stress-transport” (SST) $k - \omega$ turbulence model (Menter, 1994) are convoked for comparisons.

A. Fully-Developed Turbulent Channel Flow

Fully-developed turbulent channel flows at $Re_x = (395; 640)$ are computed to substantiate the ZEM efficacy in replicating the near-wall turbulence. The DNS (direct numerical simulation) data are available from Refs. (Mansour et al., 1988 and Kawamura et al., 1999) for this test case. A one-dimensional (1-D) RANS solver with the pressure-velocity correction method (Rahman et al., 1996 & 1997 and Rahman, 2020) has been used to conduct the simulations in a channel half-width. The chosen mesh resolutions $1 \times 64$ and $1 \times 128$ grids are respectively for $Re_x = 395$ and $Re_x = 640$. Both grid arrangements are presumed to be perfect enough to reproduce the characteristic flows. The first neighbouring cell centre is at $y^+ \approx 0.3$ to ensure the viscous sublayer resolution.

Figure 1 and 2 show the computations in wall units from the ZEM and SST models. Results are plotted as: $u^+ = u/u_\infty, \quad uv^+ = uv/u_\infty^2, \quad k^+ = k/u_\infty^2$ and $\varepsilon^+ = \nu \varepsilon/u_\infty^2$ against $y^+$. The “Boussinesq approximation” has been used to calculate the Reynolds shear stress $(\overline{uv})$. Remarkably, reasonable predictions of mean velocity profiles in Figs. 1(a) and 2(a) are obtained when compared with DNS data, although the ZEM neglects the transport and diffusion effects of $k$ and $\varepsilon$. In contrast, the SST model under-predicts the mean velocity profiles in the wake-deficit region of BL at $Re_x = 640$. This deficiency perhaps arises owing to its improper choice of closure coefficients. Figures 1(b) and 2(b) represent the Reynolds shear stress profiles; both the ZEM and SST turbulence model fairly match DNS data, as can be observed.

Figure 1(c) and 2(c) execute a further assessment of the model performance with the $k^+$ profiles. Indicative plots of $k_a^+$ and $k_b^+$ from Equations (9) and (11) are also displayed, which have good correspondence with DNS data in the viscous sublayer and log-layer regions. As can be noticed, the ZEM fairly agrees with DNS data, whereas the SST model badly underestimates the $k^+$ profile in the near-wall region. Figure 1(d) and 2(d) compare the $\varepsilon^+$ profiles from both turbulence models with DNS data. Note-worthily, both models are incapable of capturing the maximum magnitudes of $\varepsilon^+$ at the wall, approved by DNS and experimental data. However, they predict the $\varepsilon^+$ profiles qualitatively well after the wall region. In fact, such a behaviour of the $\varepsilon^+$-profile is admitted by the SST in near-wall regimes to enhance the convergence-acceleration of the numerical solver.

B. Zero pressure-gradient flat-plate BL flow

The ZEM performance is further contrasted with the measured data of the flat-plate BL flow with a free-stream turbulence intensity $Tu_{\infty} = 6.0\%$ (referred to as the T3B BL case) and a reference velocity of $U_{\infty} = 9.4\text{ m/s}$. The free-stream turbulence intensity can be given by

$$Tu_{\infty} = \sqrt{\frac{5}{3} k_{\infty}}/U_{\infty}$$

Experimental data are extracted from “ERCOFAC (European Research Community on Flow Turbulence and Combustion)” Fluid Dynamics Database.
(Savill, 1993). The free-stream eddy viscosity ratio $R_{TR} = 1.0$ is used in the current simulation. A typical non-uniform computation mesh $96 \times 64$ with a length of 1.6 m and a height of 0.3 m is shown in Figure 3. The wall-adjacent cell height is at $y^+ < 1.0$, whereas at the leading-edge point $y^+ = 2.1$. The near-wall regions retain a heavily clustered grid. The selected grid resolution is found to be convenient in assuring a grid-independent solution (Rahman, 2022). Simulations have been prosecuted with 16 cm prior to the leading edge of the flat plate, wherein a symmetric boundary condition has been endorsed.

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**Figure 1:** Mean profiles of turbulent channel flow at $Re = 395$: (a) velocity; (b) Reynolds shear stress; (c) $k$; and (d) $\varepsilon$.

**Figure 2:** Mean profiles of turbulent channel flow $Re = 640$: (a) velocity; (b) Reynolds shear stress; (c) $k$; and (d) $\varepsilon$. 

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**Figure 3:** Non-uniform computation mesh $96 \times 64$ with a length of 1.6 m and a height of 0.3 m.
Figure 4 shows the skin friction profiles \( C_f = 2\tau_f^2/U_*^2 \) for the ZEM and SST turbulence models. As is evident, both models provide fully turbulence solutions to the T3B BL case. The "dive" at the measured \( C_f \) distribution remains unpredicted since the selected turbulence models are insensitive to transition physics. The ZEM outperforms the SST in reproducing the experimental \( C_f \) profile along the fully turbulent regime.

Figure 5 represents a comparison of model predictions against measured velocity profiles of the fully-turbulent regimes at three representative positions: \( x = (0.395, 0.895, 1.495) \) m. The mean velocity profiles at both BL and weak regions are well-reproduced by the ZEM when compared with experimental data. Apparently, the differences among velocity profiles in the outer layer can be explained by the predictive nature of both the ZEM and SST turbulence model in replicating \( C_f \) in Figure 4. The Reynolds shear stress and turbulent kinetic energy are plotted together with experimental data in respective Figure 6 and 7 at the same locations. The measured total kinetic energy of turbulence is calculated using the "usual approximation \( k \approx 3/4(\overline{u'v'}) \)" as the \( \overline{w'w'} \) component is unavailable in the experiment. Conspicuously, the Reynolds shear stress profiles from both models reasonably agree with the measured data. Compared to the ZEM, the SST model underestimates the \( k \) profile in the near-wall region. The overall achievement in evaluating the friction-coefficient mean velocity and turbulence profiles is the best for the ZEM, showing an interesting feature that the ZEM agreeably mimics the measured \( k \) profile.
C. Transonic Flow Past an RAE2822 Airfoil

The transonic flow passed an RAE2822 airfoil with strong shock-wave BL interactions is computed to justify the ZEM performance. This is a well-documented test-case for validating a new turbulence model (Cook et al., 1997; Lien et al., 1998 and Singh, 2001) with the free-stream Mach number $Ma_\infty = 0.73$, Reynolds number $Re_\infty = 6.5 \times 10^6$ and angle of attack $AOA = 2.8$ deg. Transition on both upper and lower surfaces of the airfoil in the experiment has been tripped near the leading edge at $x/c = 0.03$, where $c$ is the airfoil cord length. The numerical methods and turbulence models influence the shock position and amount of separation (Singh, 2001). To simulate the RAE2822 airfoil, a nonuniform C-type structured grid $384 \times 128$ has been generated; 256 grid cells are allocated on the airfoil surface, which provide the wall-adjacent cell-centre at $y^+ \leq 1.0$. To better reproduce the leading-edge curvature, grid points are carefully arranged therein. Figure 8 shows the computational mesh with zoomed and full views. Far-field boundary conditions are prescribed at 40c away from the airfoil surface where viscous wall-boundary conditions are applied. At free-stream boundaries, $Tu_\infty = 0.1\%$ and $R_{\gamma\infty} = 1.0$ are set. Computations are performed such as to match the experimental lift $C_L$ and drag $C_D$ coefficients, a criterion to judge the convergence.

A grid dependency study is conducted with two different grid resolutions, as shown in Figure 9. Except along the shock position indicated by the vertical lines on $C_p$ and $C_f$ curves, results appear to be almost grid-convergent on two-mesh levels. Therefore, a grid-independent numerical solution has been presumably ensured by the fine $384 \times 128$ non-uniform grid resolution. Figure 10 demonstrates $C_p$ and $C_f$ coefficients together with measured data (Lien et al., 1998; and Singh, 2001). It is clear from Figure 10(a) that the “roof-top pressure” is fairly reproduced, the shock location is predicted slightly upstream of the experimental location by the SST model and the “post-shock pressure recovery” is agreeably captured. The $C_p$ profiles on the pressure side (lower surface of the airfoil) give similar impressions to the measured data. Figure 10(b) indicates
that $C_f$ profiles from both models have decent match with measured data and capture the sudden change in $C_f$ at the shock location. The ZEM detects a tiny shock-induced separation zone; however, the SST model has missed this aspect. Perhaps, the shock is too weak for the SST model with this test case to induce separation, although it is expected that the shock-induced separation may occur due to the existence of the adverse pressure gradient. Apparently, the SST turbulence model inaccurately predicts the eddy-viscosity at the shock location, causing to miss the separation. However, the ZEM captures the “essence of wall turbulence”, signifying that the stress length (with the universal multi-layer formulation) defines the invariant wall normal distribution of the eddy-viscosity, facilitating to replicate the shock-induced separation. Due to the availability of only one measured data point on the pressure side (bottom surface) of the airfoil, no detailed comment can be made regarding the $C_f$ coefficients. Table 1 reports the predicted $C_L$ and $C_D$ values from both models with measured data [26]. Qualitatively, the computed values of lift and drag coefficients from both models match the measurements.

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**Figure 8:** Computational grid for RAE2822 airfoil: (a) near-field view; (b) full view

**Figure 9:** Effect of grid density on RAE2822 airfoil: (a) pressure coefficient profiles; (b) skin friction profiles.
4. CONCLUSIONS

Turbulent channel and flat-plate BL flows are computed to substantiate the ZEM efficacy in reproducing the near-wall turbulence. The RAE2822 airfoil is simulated to justify the model ability in capturing anisotropic flows with shock-wave BL interactions. Results advocate that the ZEM is competitive with the widely-used SST model. A general multi-layer representation of the stress length $l_{12}$, adhering to the physics of wall turbulence defines the wall-normal invariant of $T^w$; this aspect facilitates the success of the ZEM. The multi-layer ZEM provides an optimistic view of the RANS turbulence modelling to enhance prediction accuracies by the essence of wall turbulence. Specifically, the ZEM may induce plausible constraints on unsteady RANS, large-eddy and detached-eddy simulations.

Remarkably, the multi-layer parameters such as $l_{12}^0$ and $y_{buf}^+$ identify the relevant flow physics of turbulent BL and the ZEM can be used to modify them for turbulence and transition modelling with the availability of experimental data.

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Numerical Modeling of Low-Velocity Impact on Composite Laminates

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ABSTRACT

The response over the low-velocity impact of various shape impactors on a glass fiber reinforced polymer composite has been numerically analyzed with a hemispherical, flat, partially flat and truncated shaped impactor used to analyze the behavior of resistance of a GFRP composite at various speeds. The numerical analysis was carried out using finite element analysis software, ABAQUS (Dynamic/Explicit). To assess the response of the composite laminates while impacting, finite element models were developed. The Hashin failure criteria were used to represent braided glass-fiber reinforced composite plate damage. Regarding projectile shape, the impact reaction of the composite was examined. The results also show that the mechanical response of woven glass fiber polymer composite under low-velocity projectile impact largely depends on the impactor’s nose shape and the velocity of the impactor.

1. INTRODUCTION

A composite material is a macroscopic blend of two or more distinct materials with a distinguishable interface. A laminate composite's distinguishing feature is its high basic strength (Sevkat et al., 2009). A plastic polymer resin is used to combine thousands of tiny glass strands into fiberglass and bind them rigidly in place. Epoxy, Polyester, Vinyl ester, Polyurethane and Polypropylene are some of the most common plastic resins used in composites (Thiagarajan et al., 2012). According to Sjoblom et al. (1988) and Shivakumar et al. (1985), low-speed impacts are quasi-static events involving upper limits that can vary from one ms⁻¹ to ten ms⁻¹ depending on the mass and stiffness of the impactor, the stiffness of the target, and perhaps other criteria. The low-velocity effect, the structurally dynamic reaction of the target, is crucial because the contact time allows the entire system to react to the hit, increasing the amount of energy elastically absorbed. (Sjoblom et al., 1988) (Shivakumar et al., 1985). The laminate's impact resistance is determined by various parameters, including inter-laminar strengths, stacking sequence, impacting item size, velocity and mass of the impactor. Whenever a structure comprised of composite material is in interaction with a foreign object, fiber breakage, delamination, matrix cracking, and plastic deformations due to contact are only a few effects to consider (Richardson & Wisheart, 1996). Materials in the matrix phase are usually continuous. A foreign body has an influence on the composite material (Singh & Shinde, 2022). Liu and Malvern (1987) proposed that the type of impact can be classified based on the amount of damage sustained, particularly if damage is the primary concern. Penetration-induced fiber breakage characterizes high velocity, while delamination and matrix cracking characterize low velocity (Liu & Malvern, 1987). Robinson and Davies (1992) used laboratory coupon testing results to examine the damage tolerance of brittle composite structures, analyzing the effect of impactor weight and specimen design size on the low-velocity impact performance of a variety of woven fiber reinforced composite laminates. Safri et al. (2014) illustrated the deformation and damage mechanisms involved throughout the impact of objects in formulating appropriate composite structures to improve the survivability of aircraft structures regarding low and high-velocity impacts. For epoxy composites, this results in the transition to the impact of energy can be measured if height and weight are known. Though appropriate techniques for detection can be used for quantification. The seriousness of such losses could be low-speed impacts considered to be dangerous loads because they influence the efficiency of the composite (Cawley, 1989) (Amaro et al., 2012). Kurşun et al. (2016) was using an experimental procedure and ABAQUS validation to investigate the impact issue, establishing that impactor shape has a major impact on damage pattern and stress distribution. They also discovered that with a low-
velocity impact, a flat cylindrical impactor generates the maximum damage to the laminate, whereas a smaller contact area causes less damage (Kursun et al., 2016). Finite element measurements have been extrapolated to composites of multiple shapes, compositions, sizes, forces, and boundary conditions, without incurring the cost and time associated with physical processing. Once validated with experimental evidence, FE models may yield incredibly valuable findings in a wide range of scenarios (Moura & Marques, 2002) (Sridhar & Rao, 1995). Hosur et al. (2005) performed a test for low-speed impacts with a hemispherical impactor on thin hybrid composites. They found that the carriage performance of hybrid composites was increased considerably in contrast to carbon/epoxy strains with a marginal decrease in rigidity (Hosur et al., 2005). Another study presented the energy of impact, the diameter of the impactor and sandwich boards, such as the core thickness of the foam and thickness of the face boards on impact behavior and impact damages (Wang et al., 2013). The impact response of two hybrid composites with comparable glass and graphite fabric compositions but different lay-up arrangements were investigated by Sevkat et al. (2013). The results indicate a higher force, greater delamination among hybrid layers and short contact duration for impactors with a larger contact surface (Sevkat et al., 2013). Zhou (1995) has had a low-speed effect with a flat-ended impactor on glass-enhanced laminates made of tissue. The structural features of these structures for impact damage are influenced by geometry (Zhou, 1995). Mitrevski et al. (2006) investigated the impact of impactor on the effects of thin tissue laminates carbon-epoxy experimentally. The various impactor forms have greatly impacted mechanisms for damage (Mitrevski et al., 2006). A research study investigated the impact response of woven glass–epoxy laminates, and their findings illustrate the impact and Compression After Impact (CAI) influence of the projectile diameter (Icten et al., 2013). The glass/epoxy-laminated composite plate's low-velocity impact loading behavior was examined in relation to the effect of biaxial preloading experimentally and numerically (Kursun et al., 2015). Drop weight impact is used in experimental tests for low-velocity effect, and the weights may be of various shapes, as well as a pendulum type test. Another research study investigated the LVI phenomenon on hybrid composite beams using the Charpy effect method (Rawat et al., 2017). Sevkat et al. (2013) investigated the effects of drop weight on hybrid composites. The analysis was focused on experimentation and was validated using LS-DYNA (Sevkat et al., 2013). Shashikumar (2015) investigated the performance of glass fiber reinforced polymer composite laminates under the low-velocity influence using the explicit finite element analysis tool LS-DYNA. The numerical and analytical conclusions were compared to existing experimental data from the literature study regarding overall impact force and energy. The variation in empirical, laboratory and analytical values was less than 10%, suggesting that the results were within a reasonable estimation range (Shashikumar, 2015). Bouvet et al. (2012) used a numerical model to capture the various types of damage that can occur in composite laminates when they are subjected to a low-velocity/low energy impact. Three types of damage were considered in their numerical model: fiber failure, matrix cracking and delamination (Bouvet et al., 2012). There is a scarcity of studies that examined the influence of impactor shapes on the impact response of composite sandwich plates, necessitating the collection of more data on the response of sandwich structures to low-velocity impact. Therefore, a numerical investigation on the glass fiber reinforced polymer composite to analyze the behavior of resistance of a GFRP composite at various speeds of energy impact.

Modeling the composite as an orthotropic elastic material allowed for the preliminary elastic response of the woven glass fiber laminate to be identified. The values of elastic modulus $E_{11}, E_{22}, E_{33}$, Poisson's ratios $\nu_{12}, \nu_{13}, \nu_{23}$ and shear modulus $G_{12}, G_{13}, G_{23}$ are utilized to describe the composite. The density of the glass fiber was calculated to be 1,800 kg/m$^3$. The mass of all impactors is 1.5kg and is assigned to the reference point of the impactor.

2. MATERIALS AND SYSTEM MODELING

The composite investigated in this simulation comprised of four plies of GFRP composite laminates, where each ply was 0.1 mm thick. The fiber orientation of this composite is 0/90/90/0. The dimension of the GFRP composite laminate is 72mm x 72 mm.

![Figure 1: Dimension of GFRP composite plate](image)

The numerical model was analyzed using four distinct types of impactors. All of these impactors’ dimensions are specified in millimeters, and the complete length of these impactors from top to bottom surface is 30 mm. Epoxy polymer matrix is used in this glass fiber polymer composite. Uniform requirements might be used with an element removal technique for damage initiation to remove Abaqus rejected elements. Below are the values for $X^T, X^C, Y^T, Y^C, S^t, S^c$.

<table>
<thead>
<tr>
<th>$E_1$</th>
<th>$E_2$</th>
<th>$E_3$</th>
<th>$V_{12}$</th>
<th>$V_{13}$</th>
<th>$V_{23}$</th>
<th>$G_{12}$</th>
<th>$G_{13}$</th>
<th>$G_{23}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>23</td>
<td>5</td>
<td>.15</td>
<td>.15</td>
<td>.15</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1: Properties of the glass fiber laminates utilized in this study (Fan et al., 2011)
Figure 2: (a) Truncated Impactor (b) Hemispherical Impactor (c) Partially flat Impactor (d) Flat Impactor

Table 2
Damage initiation data of the glass fiber laminates utilized in this study (Fan et al., 2011)

<table>
<thead>
<tr>
<th>X_T (MPa)</th>
<th>X_C (MPa)</th>
<th>Y_T (MPa)</th>
<th>Y_C (MPa)</th>
<th>S_L (MPa)</th>
<th>S_T (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>320</td>
<td>240</td>
<td>320</td>
<td>240</td>
<td>320</td>
<td>320</td>
</tr>
</tbody>
</table>

X_T and X_C represent tensile and compressive strengths in the longitudinal direction. Y_T and Y_C represent tensile and compressive strengths in the transverse direction. S_L and S_T represent longitudinal and transverse shear strengths.

After damage initiation, the negative slope of equivalent load-displacement relation is used to simulate damage progression. The value required for damage progression is given below.

Table 3
Fracture energies for damage progression of composite laminate (Fan et al., 2011)

<table>
<thead>
<tr>
<th>Longitudinal tensile fracture Energy (J/m^2)</th>
<th>Transverse tensile fracture Energy (J/m^2)</th>
<th>Longitudinal compressive fracture Energy (J/m^2)</th>
<th>Transverse compressive fracture Energy (J/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40000</td>
<td>40000</td>
<td>60000</td>
<td>60000</td>
</tr>
</tbody>
</table>

This investigation defined contact and interaction using a general contact method and a contact pair algorithm. Both methods use advanced tracking algorithms to ensure that adequate contact conditions are properly maintained and they may be employed concurrently in a model. To simulate the interaction between GFRP plates subjected to projectile impact, a surface-to-surface contact pair was created between the projectile surface and the nodes-set at the target center of each layer. In contrast, a general contact interaction was constructed between the two adjacent layers. The contact interaction characteristics applied in this study are presented in Table 4.

A. Modeling Progressive Damage

There are four main modes of failure (though several others may be referred to) since fiber-reinforced plastic (FRP) laminates are heterogeneous and anisotropic: mode-cracking matrix happens in parallel with fibers because of stress, compression or shear, mode-derived, delamination of inter-laminar strain, fiber splitting and un-compressed fiber buckling mode-in-tension fiber, the impactor perforates the impacted area completely. Identify the fault mode since this would provide information not only on the impact event but also on the residual intensity of the structure. In understanding damage mode starts and develops, interactions between failure modes are also significant. Applying Hashin’s failure criterion, the composite's damage initiation was designed. These criteria use a total of four different types of damage-initiation mechanisms: matrix tension, matrix compression, fiber tension, and fiber compression. The initial failure criteria are as follows:

Fiber tension:

\[ F_{f}^{T} = \left( \frac{\sigma_{11}}{X_{T}} \right)^{2} + \left( \frac{1/2}{X_{C}} \right)^{2}, \sigma_{11} \geq 0 \]  

(1)

Fiber compression:

\[ F_{f}^{C} = \left( \frac{\sigma_{11}}{X_{C}} \right)^{2}, \sigma_{11} < 0 \]  

(2)

Matrix tension:

\[ F_{m}^{T} = \left( \frac{\sigma_{22}}{Y_{T}} \right)^{2} + \left( \frac{1/2}{Y_{C}} \right)^{2}, \sigma_{22} \geq 0 \]  

(3)

Matrix compression:

\[ F_{m}^{C} = \left( \frac{\sigma_{22}}{Y_{C}} \right)^{2} + \left( \frac{1/2}{Y_{T}} \right)^{2} - 1 \left( \frac{\sigma_{22}}{Y_{C}} \right)^{2} + \left( \frac{1/2}{Y_{T}} \right)^{2}, \sigma_{22} < 0 \]  

(4)

The damage elastic matrix can be represented as,
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\[ C_d = \frac{1}{D} \begin{bmatrix} (1 - d_f)E_1 & (1 - d_f)(1 - d_m)v_{12}E_1 & 0 \\ (1 - d_f)(1 - d_m)v_{12}E_2 & (1 - d_m)E_2 & 0 \\ 0 & 0 & (1 - d_s)GD \end{bmatrix} \] (5)

\( \bar{\sigma}_{11} \) is the longitudinal effective stress tensor component, \( \bar{\sigma}_{22} \) is transverse effective stress tensor component and \( \bar{\tau}_{12} \) is shear effective stress tensor component and \( \alpha \) represents the contribution of shear stress to the fiber tensile initiation criterion. \( G \) is the shear modulus, while \( D \) is the total damage variable, linking stress and strain to demonstrate stress deterioration. In the equation above, \( d_f \) stands for the current state of fiber damage, \( d_m \) for the current state of matrix damage, \( d_s \) for the current state of shear damage, and \( C_d \) for the current state of the damaged elastic matrix.

Table 4
Contact interaction properties used in this study (Fan et al., 2011)

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Contact Algorithms</th>
<th>Friction Formulations</th>
<th>Friction-coefficient</th>
<th>Pressure Overclosure</th>
<th>Contact-stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impactor-GFRP</td>
<td>Contact pair</td>
<td>Penalty</td>
<td>0.6</td>
<td>Hard</td>
<td>Hard</td>
</tr>
<tr>
<td>GFRP-GFRP</td>
<td>General-contact</td>
<td>Penalty</td>
<td>0.3</td>
<td>linear</td>
<td>15 GPa</td>
</tr>
</tbody>
</table>

Through numerical modeling using the ABAQUS software, the stress distribution on the GFRP laminate as a result of the low-velocity impact will be determined (Dynamic, Explicit). Development and use of sophisticated numerical techniques based on the Finite Element Method are among the project's endeavors (FEM). The effect of material constants on the stress singularity will be examined using the developed numerical model. Geometry modeling was done initially. There was a 0.1 mm distance between the impactor tip and composite plate top surface, so there may not occur any initial damage. Then the plate's characteristics were unveiled. Following the creation of the step, the model's boundary conditions were applied. The side face of the composite plate is fixed (U1=U2=U3=0). The impactor's only allowed direction of movement is in the Z direction. Neither axis is rotated, as well as no X or Y movement. The weight is assigned at the impactor's reference point. Different speeds are supplied as a predefined value for the loading situation. Meshwork was the last phase. The element shape for composite laminate is Hex, and the technique was structured. Reduced integration with hourglass control, an 8-node quadrilateral element type of the meshing is R3D4: A 4-node 3-D bilinear rigid quadrilateral.

3. RESULT AND DISCUSSION

A. Mesh Sensitivity Analysis
The element size is maximum on the edge of the composite laminates and minimum in the center of the composite laminates. The maximum size is 1 mm, and the minimum size is 0.75 mm. As element size decreases, the peak load of this model also can be observed. Peak load values for element sizes of 0.5 mm, 0.25 mm, and 0.1 mm are nearly constant having started at 0.75 mm element size.

![Figure 4: Mesh Independency test](image)

B. Model Validation
The numerical data was validated with experimental data and the final model was developed. The graph plotted in Figure 5 shows the FE and experimental curve of impact load on the composite plate against time. For both conditions, the peak load was almost similar. But, there is a little discrepancy between the numerical result and the experimental results in the case of time. This happened due to not assigning the velocity-time amplitude. The velocity-time data was not given the pre-determined velocity used in the loading condition. Because of this numerical model graph was slightly different from the research paper load against the time graph.

![Figure 3: Geometrical modeling of low-velocity impact on GFRP composite laminate](image)
in-plane general-purpose continuum shell, and finite membrane stresses make up the SC8R element type used in the meshing. The element shape for all four impactors is Quad-dominated, and the technique was a sweep. The

![Figure 5: Geometrical modeling of low-velocity impact on GFRP composite laminate](image)
Figure 5: Simulation result and experimental (Fan et al., 2011) work comparison based on load against time

Figure 6: Load v/s Time at (a) 0.5 ms⁻¹ (b) 1 ms⁻¹ (c) 1.5 ms⁻¹ (d) 2 ms⁻¹ (e) 2.5 ms⁻¹ velocity
The load-time curves of four distinct types of impactor’s low-velocity impact on the composite plate at different velocities are illustrated in Figure 6. The load-time curves have parabolic shapes, and the maximal contact force is greatest when the impact energy is low and increases as the impact energy does. The response force applied from the specimen to the impactor is sometimes called the contact force. As was already noted, all information was gathered using the ABAQUS program to determine how the contact force varied with contact time. Due to its enormous surface area, the flat impactor produces the maximum peak load. The peak load of a partially flat impactor is hence lower than the flat impactor because the tip surface area is less than the flat impactor. Since it has a smaller surface area, the truncated impactor’s peak load is less than that of the partially flat and flat-shaped impactor. Since the hemispherical impactor's tip surface area is the lowest, it produces the lowest peak load among the four impactors. As seen in Figure 6 sequentially, it is clear that the peak load increases with increasing velocity and the graph pattern changes slightly. Stress was produced throughout the perimeter owing to shear force for impactors with flat, partially flat, and truncated shapes that struck the top surface of composite plates. In contrast, the center of a hemispherical-shaped impactor produces stress when it makes contact with the plate top surface.

All four plies of the composite plate experienced internal stress as a result of the collision and comparatively at a greater velocity, di-lamination in the composite plate was initiated.
Figure 7 depicts displacement versus time curves for four distinct shaped impactors at 0.5 \( \text{ms}^{-1} \), 1 \( \text{ms}^{-1} \), 1.5 \( \text{ms}^{-1} \), 2 \( \text{ms}^{-1} \), and 2.5 \( \text{ms}^{-1} \), respectively. Hemispherical impactor has the maximum displacement: As it has the least tip area, stress is concentrated and displacement is high. A little less displacement is produced by the impactor truncated, and the somewhat flat impactor produces even less. The impactor with a flat form has the least displacement because the tip surface area of the flat impactor is the biggest among them. With increasing time, displacement increases gradually, but after maximum, displacement decreases with increasing time as the impactor returns to the initial position and some impactor ray beyond the initial position at comparatively higher velocity.

Figure 8 shows the total energy of the whole model against the time graph plotted for four distinct shaped impactors at 0.5 \( \text{ms}^{-1} \), 1 \( \text{ms}^{-1} \), 1.5 \( \text{ms}^{-1} \), 2 \( \text{ms}^{-1} \), and 2.5 \( \text{ms}^{-1} \), respectively. As seen in Figure 8 impactor hit the composite plate with the initial kinetic energy of 0.1875J, 0.75J, 1.6875J, 3J, and 4.6875J sequentially. During an impact event, the energy absorbed by the laminates is dissipated through the damage formation. Initially, energy increases over time because of increasing strain energy of the plate, but after attaining maximum energy, the energy declines over time due to creep, friction and damage absorption. Among all impactors, energy variation tends to be identical at relatively high velocities.

4. CONCLUSIONS

The low-velocity effect on the GFRP composite has been quantitatively modeled in this experiment using the finite element analysis software ABAQUS. This model was developed to compare the variation of energy for the entire model and study the stress field of the composite plate at different velocities for various shape impactors. Since a flat-shaped impactor has the maximum contact time with the least amount of displacement, it also carries the most stress on the contact surface. The hemispherical shape impactor has the least amount of contact time with the greatest amount of displacement, generating the least amount of stress on the contact
surface. In this research, five different pre-determined velocities were assigned to all impactors, and it was seen that with increasing velocity load in the contact surface and displacement increase. Also, with increasing velocity, the energy variation with respect to time tends to be indistinguishable for all four impactors. For truncated, partially flat and flat impactors stress is generated where the impactor’s perimeter hits the plate, and for hemispherical impactors, stress is generated in the center of the composite plate where impacted. The inter-laminar stress field was also analyzed, and it was seen that delamination between plies occurred with increasing velocity.

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Importance of Stress and Temperature-Dependent Permeability of Rocks and its Application in Underground Nuclear Waste Disposal

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ABSTRACT

Water flow is an essential factor in the sealability of any underground cavern, including those for nuclear waste disposal, and is significantly affected by the permeability of the rock. The permeability of rocks is affected by various factors, including stress and temperature. The rock stress changes by excavating a cavern, and rock temperature changes by decay heat from nuclear waste, and the temperature change induces thermal stress. Therefore, water flow around such caverns must be evaluated considering the effects of stress and temperature. Numerical analyses of water migration around underground nuclear waste disposal caverns have been carried out. However, studies considering the stress and temperature-dependent permeability may not be published yet. To demonstrate the necessity to consider the stress and temperature-dependency in permeability, equations that represent the post-failure permeability as a function of average effective stress and temperature were proposed. The water inflow was numerically calculated for a simple underground nuclear waste disposal cavern with or without stress and temperature dependency which showed the significance of the dependency. Also, the importance of rock types was demonstrated by considering the three rocks of granite, sandstone, and tuff for a full-scale underground radioactive disposal site for the stress and temperature-dependent permeability. A high sealability could be expected for granite and sandstone but not for the tuff. Introducing the stress and temperature-dependent permeability could contribute to the thoughtful design of an underground repository for radioactive waste disposal considering rock types.

1. INTRODUCTION

In the sealability of any underground cavern, including those for nuclear waste disposal, water flow is an essential factor. It is significantly controlled by the permeability of the rock. The permeability of rocks is affected by various factors, including stress and temperature. For example, the results of a series of permeability measurements for three rock types under confining pressure between 1 - 14 MPa at 22°C/ 295 K and 80°C/ 353 K were given by Alam et al. (2014 and 2015). The excavation of a cavern changes the rock stress and decay heat from cesium, strontium, americium, curium etc. in nuclear waste changes the rock temperature. The thermal stress is induced by the temperature change (Figure 1). Therefore, water flow around such caverns must be evaluated considering the stress and temperature effects. Numerical analyses of water migration around underground nuclear waste disposal caverns have been carried out. For example, Bian et al. (2012) numerically calculated the thermo-hydromechanical behavior of the surrounding rock mass of micro tunnels for high-level nuclear waste disposal in Callovo-Oxfordian claystone formation by FLAC3D, which is a commercial code adapting fast Lagrangian analysis provided by Itasca Consulting Group using finite-difference method (FDM).
Kwon et al. (2013) studied thermal stress distribution around canisters containing nuclear wastes and applied the solutions to consider bentonite inclusions by FLAC3D. Yu et al. (2017) derived analytical solutions for thermo-hydro-mechanical behavior of rock mass around a heating hole and PRACLAY and ATALS III heating tests—however, none of these studies considered the stress and temperature-dependent permeability.

This paper does not aim to perform a detailed thermo-hydro-mechanical numerical analysis for a specific site’s rock mass but to show the general importance of taking into account the stress and temperature dependency in the water migration analyses around underground nuclear waste disposal caverns and how to apply it in a mined-repository for nuclear waste. First, we propose equations describing post-failure permeability as a function of average effective stress and temperature based on Alam et al. (2015)’s experimental results. The post-failure permeability here refers to the permeability of rocks that have fractured and reached the residual strength state. Rock masses are fractured and have much higher permeability than intact rocks. The difference in permeability between rock masses and post-failure rocks is likely to be much smaller than that between rock masses and intact rocks. It can also be said that measuring the post-failure rock’s permeability is much more feasible than measuring the intact rock’s permeability because the former is much higher than the latter, primarily for hard rocks. We then calculate the water migration into a simple underground nuclear disposal cavern with a 2-D elastic FEM (Finite Element Method) and explain the results. Based on these results, we present the water inflow around the underground repository for radioactive waste, showing the potential of radio nuclide migration by groundwater, showing the importance of rock type.

2. MATERIALS AND METHODS

For the experiment, Inada granite, Kimachi sandstone, and Shikotsu welded tuff were selected, covering a wide range of rock physical properties (Table 1). The commercially available intact rock blocks were used for the experiments. The Shikotsu welded tuff from Hokkaido, Japan, contains plagioclase, hypersthene, augite, hornblende, and transparent glass. All these minerals are relatively small in grain size. The grains of each mineral were smaller than 1 mm.

The Miocene Kimachi sandstone from Shimane, Japan, has mostly andesite rock fragments and some minerals like plagioclase, pyroxene, hornblende, biotite, and quartz. The matrix also has calcium carbonate, iron oxides, and zeolites. It is a clastic rock with good-sorting grains sizing about 0.4–1.0 mm (Dhakal et al., 2002).

The main minerals in the Paleocene Inada granite from Ibaraki, Japan, are quartz, feldspar, biotite, and allanite. It also has some zircon, apatite, and ilmenite (Lin et al., 2008). The minerals have different grain sizes: quartz is about 3.0–4.0 mm, plagioclase and alkali feldspar are about 2.0–3.0 mm, and biotite is usually smaller than 1.0 mm.

The specimens, which were 30 mm in diameter and 60 mm long, were fully saturated in de-ionized water in a water-submersible vacuum jar before two stainless steel
endpieces were taped to the saturated specimen. A hole was drilled through the center of each endpiece for water flow to the specimen. A layer of silicone sealant prevents the water from flowing inside the specimen. The specimen and the associated endpieces were then covered with a heat-shrinkable tube to prevent the confined fluid from permeating into the specimen. The sample was then immersed for 24 hours in de-ionized water.

The samples were put in a triaxial cell (Alam et al., 2014) with a heater and a controller around them (Figure 2). The tests were done at 22°C/295 K or 80°C/353 K with different pressures from all sides (1–15 MPa). The pressure values matched the pressure from the weight of the rock above them between 58–814 m deep. We assumed that the rock was fully saturated and weighed 27 kN/m$^3$ and that the water level was at the ground level. The highest temperature (80°C) was what we expected for the rock around a nuclear waste site (Kwon et al., 2013). It was also the highest temperature that the triaxial cell could handle.

Figure 2: Triaxial vessel with heat facility

A screw-type Instron 5586 loading frame was used for loading. Syringe pumps were used to apply confining pressure and pore pressure.

Following consolidation, a steady compression rate of $10^{-5}$ s$^{-1}$, or 0.036 mm/min, was used to increase the strain until it reached 10% for Shikotsu welded tuff or 7% for Kimachi sandstone and Inada granite. To attain the stable residual strength state, high strain values were used.

We used different methods to measure the permeability of three types of rocks. For Shikotsu welded tuff, we applied the constant flow method. While for Kimachi sandstone and Inada granite, the transient-pulse method with Brace et al.’s (1968) approximate solution was used. We recorded the load, stroke, pore pressure, confining pressure, and flow rate every 10 s on a data logger during the experiment. Micrographs from blue-resin-infused specimens were prepared to observe the structural changes under stress and temperature.

3. POST-COMPRESSION ROCKS AND THE PERMEABILITY

A. Micrographs of Post-Compression Rocks

The rock specimens of post-compression were saturated in blue resin to observe the pores and fractures. Afterward, the microscopic slides were prepared from the blue-resin-infused specimens by using mineralogic slide preparation units performing cutting, grinding and polishing. The blue colors in the micro-graphs represent the open spaces.

Figure 3: Micrographs after compression at confining pressures in increased temperature, (a) Inada granite, (b) Kimachi sandstone, and (c) Shikotsu welded tuff

In Inada granite, broad rupture planes with a network of microcracks were observed at a lower confining pressure of 1 MPa at 295 K. The comprehensive network of microcracks in rupture planes at 1 MPa 295 K and the network is narrower for 1 MPa 353 K in Inada granite.
In contrast, a wide rupture plane with larger pores (approx. 1 mm) was observed at 1 MPa 295 K, which is narrow with small pores (approx. less than 0.5 mm) at 1 MPa 353 K in Kimachi sandstone (Figure 3). The number of pores was higher at 15 MPa 295 K than at 15 MPa 353 K in Shikotsu welded tuff (Figure 3).

B. Post-Failure Permeability of Rocks as a Function of Stress and Temperature

As shown in Figure 4, the permeability after failure was inversely related to average effective stress (AES, \( \sigma' \), MPa), which was derived from Equation (1) using the residual strength (\( \sigma_r \)), pore pressure (\( P_p \)), and confining pressure (\( P_c \)).

\[
\sigma' = \frac{\sigma + 2P_c}{3} - P_p
\]

\( \text{Figure 4: Temperature and stress effects on permeability in Inada granite} \)

Shikotsu welded tuff and Inada granite had higher and more stress-sensitive permeability after failure at 295K (\( K_1 \)) than at 353K (\( K_2 \)). However, for Kimachi sandstone, the permeability difference was slight, and the stress dependency was similar at both temperatures. The equations below show the relationship between the permeability and the \( \sigma' \) for rocks.

\[
log K_1 = A_1 + B_1 \sigma' \text{ at } T_1
\]

\[
log K_2 = A_2 + B_2 \sigma' \text{ at } T_2
\]

\[
A_1 = log a_1
\]

\[
A_2 = log a_2
\]

Here \( a_i \) is the regression line's y-intercept, and \( B_i \) is the stress sensitivity at \( T_i \) (Figure 5). Temperature influences on permeability \( A (-), B (\text{MPa}^{-1}) \) can be seen in the differences between \( a_1 \) (permeability at \( T_1 \) under \( \sigma' = 0 \)) and \( a_2 \) (permeability at \( T_2 \) under \( \sigma' = 0 \)) or between \( B_1 \) and \( B_2 \). Compared to sandstone, they are significantly more prominent for granite and tuff (Figure 5, Table 2). Equations (6 to 8) were derived assuming linear correlations between temperature and the constants to represent the stress and temperature-dependent permeability \( K \).

\[
K = 10^{A+B \sigma'}
\]

\[
A = A_1 + \frac{T-T_1}{T_2-T_1} (A_2-A_1)
\]

\[
B = B_1 + \frac{T-T_1}{T_2-T_1} (B_2-B_1)
\]

\( \text{Table 2} \)

Permeability at 295K (\( a_1 \)) and 353K (\( a_2 \)), stress dependency at 295K (\( B_1 \)), and 353K (\( B_2 \))

<table>
<thead>
<tr>
<th>Rock type</th>
<th>( a_1 ) ( \left( \text{m}^2 \right) )</th>
<th>( a_2 ) ( \left( \text{m}^2 \right) )</th>
<th>( B_1 ) ( \left( \text{MPa}^{-1} \right) )</th>
<th>( B_2 ) ( \left( \text{MPa}^{-1} \right) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shikotsu welded tuff</td>
<td>( 5.43 \times 10^{-15} )</td>
<td>( 4.91 \times 10^{-16} )</td>
<td>-0.041</td>
<td>-0.013</td>
</tr>
<tr>
<td>Kimachi sandstone</td>
<td>( 1.25 \times 10^{-17} )</td>
<td>( 8.00 \times 10^{-18} )</td>
<td>-0.034</td>
<td>-0.043</td>
</tr>
<tr>
<td>Inada granite</td>
<td>( 1.72 \times 10^{-15} )</td>
<td>( 1.22 \times 10^{-18} )</td>
<td>-0.127</td>
<td>-0.036</td>
</tr>
</tbody>
</table>

\( \text{Figure 5: The relationship between post-failure permeability and effective average stress} \)
4. SIGNIFICANCE OF TEMPERATURE- AND STRESS-DEPENDENT PERMEABILITY

The importance of stress and temperature dependency is shown by a simple 2D finite element model and full-scale model for a nuclear waste disposal cavern and applied to the underground repository for radioactive waste disposal cavern to show the scalability potential of rocks in fractured conditions. 2-D FEM (Mufundirwa et al., 2011) calculated the effect of temperature, stress, and temperature-stress coupling effects on fluid inflow into a nuclear waste disposal cavern in a rock mass at 500 m deep underground (Figure 6). The rock mass was Inada granite, and the effects of temperature, stress and their interaction on fluid inflow were investigated. The reason why the software was used is that the objective of this study is not to carry out a precise thermo-hydro-mechanical numerical for a rock mass around a specific site but to demonstrate the general necessity to consider the stress and temperature dependency in the analyses of water migration around underground nuclear waste disposal caverns as stated in the introduction. Another reason is that our research group developed this software which can be fully modified to introduce stress- and temperature-dependent permeability.

Figure 6: Underground nuclear waste disposal model

The total number of constant strain 234 triangular elements and 137 nodes were considered in this 2-D FEM. The mechanical properties used for this analysis were Young's modulus of 68 GPa, a Poisson's ratio of 0.35, a wet density of 2700 kg/m³, an expansion coefficient of 7.94×10^{-6} (K^{-1}), and effective porosity of 0.60 % (Alam et al., 2014). The backfill's effective porosity was 0.80%, Young's modulus was 69.4 MPa, Poisson's ratio was 0.22, wet density was 2100 kg/m³, and the expansion coefficient was 3.10×10^{-4} (K^{-1}) (Kwon et al., 2013). The pore pressure was considered 5 MPa, while the overburden pressure was supplied as 13.5 MPa hydrostatic pressure. The backfill's pore pressure was set to zero, assuming drainage. Since the rock mass is broken, the aforementioned post-failure permeability was applied. At the model's outside limits, a temperature of 295K was specified. A temperature of 353K or 295K was assigned to the edge of the backfill. The following steps calculated the elastic, isotropic, static, and steady solution:

- Steady temperature distribution.
- Static stress distribution considering thermal strain.
- Steady flow analysis considering the stress and temperature-dependency of the rock permeability and the temperature dependency of the water viscosity

At 295K, 36 to 43 MPa was the highest effective major stress at the cavern wall (Figure 7). The thermal stress first manifested under the same circumstances at a backfill boundary temperature increase of 353K, and the highest major stress ranged from 64 - 72 MPa, an average increase of 72%.

Figure 7: Maximum effective principal stress at 295 K (a) and 353 K (b) (compression is shown as negative)

The flow rate increase was observed in the narrow area near the opening with constant K (Figure 8a). However, higher temperature for temperature-dependent K or thermal stress for stress-dependent K at the cavern wall slows the flow rate (Figure 10b and c). The flow rate is lower for stress- and temperature-dependent K (Figure 8d). The inflow into the cavern significantly decreases (1/150) with temperature-dependent K and more so (1/500) with stress-dependent K (Figure 9). When both factors are considered, the inflow is minimal (1/2000), which is the case for a radioactive disposal mining repository.
5. WATER INFLOW IN UNDERGROUND NUCLEAR WASTE DISPOSAL IN ROCKS CONSIDERING STRESS AND TEMPERATURE-DEPENDENT PERMEABILITY

The most widely accepted idea for disposing of radioactive waste is to bury it deep underground. This involves putting the waste containers in a hole in the rock mass accessed by a tunnel.

The gap between the container and the hole is filled with bentonite buffer, while the tunnel is filled with broken rocks as backfill material. If groundwater seeps into the hole, it can carry radioactive nuclides and affect the geoenvironmental condition of the area. Therefore, the flow rate around the hole is essential to assess the geoenvironmental risk potential. Different rocks are being studied as possible repositories, such as granite (Canada, China, Finland), tuff (USA). This research considers granite, tuff, and sandstone rocks to evaluate their potential as mined repositories.

The model has (i) a 6\times4 \text{ m}^2 tunnel to access (ii) a 7\times2 \text{ m}^2 hole for disposal, and (iii) a 2\times1 \text{ m}^2 container in a 21\times14 \text{ m}^2 rock mass at 600 m depth (Figure 11), following the IAEA safety standards for geological disposal facilities for radioactive waste (IAEA, 2011). The total number of 2470 constant triangular elements and 1271 nodes applying the normal stress of 15 MPa at a depth of 500 m from the surface was considered in this simulation. Pore pressure gradient of 71 kPa/m was applied from the right to left boundaries. The flow rate in the rock mass along the 7 m side of the hole (Figure 11c) is compared to estimate the flow amount that could be the pathway for radio nuclide.

The experimental data from Table 2 was utilized in the present study to investigate the complex relationship between the rock's permeability changes and varying levels of stress and temperature for underground excavation. The researchers were intrigued by the potential of rock masses to impede the flow of water, an essential consideration for underground geological disposal, and thus, analyzed the data extensively to extract valuable insights.
Figure 10: A model of underground disposal for radioactive waste

Figure 11: Temperature condition of before (a) and after (b) decay heat in the model

Figure 12: Major effective principal stress distribution before (a) and after (b) decay heat in granite
The analysis revealed that the temperature of the disposal area experienced a significant increase from 295 K to 353 K, as depicted in Figure 11. The consequent heat transfer throughout the rock mass was complex and multifaceted, requiring a deeper understanding of the underlying principles. The rise in temperature also engendered thermal stress, leading to a substantial increase in the effective principal stress in the granite sample. The intricate details of this relationship were elucidated in Figure 12, which demonstrated a clear increase in the stress of the rock from 8-12 MPa to 12-16 MPa. Interestingly, the rise in stress was not solely due to the thermal stress but was also attributed to the decay heat, which contributed to 38% of the stress increase.

The flow rates, both within and around the excavated repository subsequent to the decay heat, as illustrated in Figure 13. The magnitude of oscillation in the flow rate was more significant for granite and tuff as opposed to sandstone. Additionally, it was discerned that the typical flow rate for tuff outpaced that of granite and sandstone, while the latter displayed the most modest average flow rate.

**Figure 13:** Fluid flow velocity around the depository before (a) and after (b) decay heat in rockmass, considering the stress and temperature dependant permeability.
The results of the simulation were found to be rather intriguing. Specifically, it was noted that the flow rate of tuff, when subjected to higher temperatures, appeared to be lower in comparison to when it was placed under lower temperature conditions. As per the gathered data, the average flow rate of tuff along the sidewall showed a reduction of a whopping 73%, which is rather significant, as depicted in Figure 10c. Interestingly, granite displayed a considerable decrease in its average flow rate when the temperature was increased from 295K to 353K (Figure 14). The recorded data showcased a decline from $1.34 \times 10^{-7} \text{ m/s}$ to $1.91 \times 10^{-9} \text{ m/s}$, which translated to a massive 99% drop in flow rate. In contrast, the average flow rate of sandstone was almost the same at both temperatures. It is imperative to note that tuff demonstrated the highest flow rate when compared to the other two types of rocks, both at higher and lower temperatures. Furthermore, sandstone presented the lowest flow rate among the three. However, at a temperature of 353K, sandstone and granite showcased relatively similar flow rates.

![Figure 14: Fluid velocity in the sidewall before and after decay heat, considering the dependency of stress and temperature on permeability](image)

6. DISCUSSION

The investigation of mathematical modeling for hydrothermal convection encompassing a radioactive waste depository in hard rock has piqued the interest of numerous researchers. Hodgkinson's research in 1980 served as a catalyst for further examination in this domain, with several research publications delving into this topic. Zhang et al. (2011) brought forth the test case 2 results of an exercise concerned with mathematical modeling for hydrothermal convection, while Liu et al. (2015) delved into the impact of compressive creep deformation on gas permeability of the porous argillite. Daniels et al. (2017) found that hydraulic properties of bentonite are exceedingly sensitive to thermal loading and the category of imposed boundary condition. Philipp et al. (2017) delved into microstructural controls on permeability for various facies of OPA.

Urpi et al. (2019) scrutinized the repercussions of thermal pressurization throughout the lifespan of a deep geological repository (DGR) for high-level radioactive waste. Plúa et al. (2021) explored the Thermo-Hydro-Mechanical (THM) responses of a porous rock with low permeability under thermal loading within the context of deep geological disposal of radioactive waste. Onee et al. (2021) investigated the methodology of modeling for fractured granite around the drift at a depth of 500 m in the Mizunami Underground Laboratory, Japan, as a case study. Ogata et al. (2021) advanced a groundbreaking framework for coupled THMC analysis employing explicit rock fracture. Sellin et al. (2013) made valuable contributions to this field with their work.

Collectively, these investigations concentrate on diverse facets of mathematical modeling for hydrothermal convection around radioactive waste depositories in hard rock. They involve the influence of multiple factors on hydraulic properties, permeability, and thermal pressurization, as well as the methodology of modeling for fractured granite. These previous researches contribute substantially to the scholarly discourse and comprehension of the complex and interdisciplinary field of nuclear waste disposal. The current investigation places a paramount focus on the intricate interplay between stress and temperature-dependent permeability of post-compression. This crucial facet of permeability, intriguingly, has been woefully disregarded in all antecedent inquiries concerning this subject matter. It is crucial to note that the nature of this intricate interplay is yet to be fully comprehended, and as such, further investigations are deemed necessary.

In the experimental results (Figure 2), the post-failure permeability negatively correlated with average effective stress. The negative correlation is because the aperture of the water paths closed with stress. The post-failure permeability at 353K was lower than 295K for all rocks. The decrease would be due to the further decrease in the aperture of the water paths by the more viscous deformation of mineral particles under the higher temperature.

However, the stress and temperature effects on the post-failure permeability differ for each rock type. The difference might be explained by considering the permeability of the rock matrix. For example, the high permeability of the porous glass matrix of the tuff at 353K did not decrease with stress because the water paths were almost closed, and water flowed in the matrix (Figure 3a). The permeability of the granite matrix is very low so that the permeability of the rock at 295K was significantly ruled by the aperture of the water paths which varied with stress (Figure 3c).

The water inflow significantly decreased in the numerical analysis results for the simple cavern model (Figure 8), considering the stress and temperature dependencies of permeability in the calculation (Figure 9) for granite. The decrease is due to stress concentration, thermal stress, and temperature rise, which means the sealability of underground nuclear waste disposal caverns may be higher than usually expected, at least at the early stages of the storage. Therefore, introducing stress and temperature-dependent permeability could contribute to the thoughtful design of those disposal sites.
Based on the outcomes, a full-scale model was considered for granite, sandstone, and tuff. For granite, the decrease in flow amount (Figure 15) at increased temperature was found as it was for the simple cavern model (Figure 9). The permeability of the granite matrix is very low, so the permeability of the rock was significantly ruled by the aperture of the rupture planes, which decreased at increased temperature (Figure 3c). The decrease was because of the more viscous deformation of mineral particles under high temperatures. For sandstone, the flow amount was not so different for increased temperature and was almost equal to that for granite. The viscoplastic deformation of cementing material of the sandstone was not enough to close the flow path (Figure 3b) at the temperature. For tuff, the flow amount slightly decreased at the increased temperature where pores were available for water migration at the temperature (Figure 3c).

Figure 15: Fluid amount in the sidewall before and after decay heat, considering the dependency of stress and temperature on permeability

7. CONCLUSIONS

To demonstrate the necessity to consider the stress and temperature-dependency in permeability, equations that represent the post-failure permeability as a function of average effective stress and temperature were proposed. For a simple underground nuclear waste disposal cavern, the water inflow was predicted using a 2-D elastic FEM with or without the stress and temperature dependency into account for granite. The results showed that the fractured rock permeability near the cavern became lower due to stress concentration, thermal stress, and temperature rise, and water inflow became significantly less for granite, which demonstrates that the introduction of the stress and temperature-dependent permeability could contribute to the thoughtful design of those disposal sites.

Among the three rocks for a full-scale underground radioactive disposal site in granite, sandstone, and tuff considering the stress and temperature-dependent permeability, a high scalability could be expected for granite and sandstone but not for the tuff.

The conclusion in this study was obtained, of course, from the limited rock types and conditions. Extensive experiments under various conditions for various types of rock may be needed. The stress and temperature-dependent permeability concept should be introduced for a wide variety of more practical scenarios, such as a transient analysis for the water migration around a cavern constructed in a rock mass with a hydraulic gradient.

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Prevalence of Multidrug-Resistant *Salmonella* in Raw Salad Vegetables in Dhaka Metropolitan Area

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**ABSTRACT**

Raw salad vegetables have become very popular among consumers due to their multiple health benefits. The bacteriological quality of these salad vegetables is of great public health concern. This study was conducted to determine the presence of potential pathogenic and multidrug-resistant (MDR) bacteria in raw salad vegetables served in different restaurants in Dhaka, the capital city of Bangladesh. A total of 50 samples, comprising different types of raw salad vegetables were collected from restaurants in Mirpur (n=10), Dhanmondi (n=10), Old Dhaka (n=10), Gulshan (n=10) and Bashundhara Residential Area (n=10). The highest counts for total coliforms and fecal coliforms were 4.02 × 10³ cfu/ml and 1.3×10³ cfu/ml, respectively. The isolates were *E. coli*, total coliform, fecal coliform and *Salmonella* spp. Among them, fecal coliform and *Salmonella* spp. were found to be more pathogenic. As potential pathogenic bacteria, *Salmonella* spp. were tested for antibiotic sensitivity and all of them showed resistance against amoxicillin, ampicillin, azithromycin, chloramphenicol, ciprofloxacin, erythromycin, kanamycin, streptomycin, tetracycline, norfloxacin, and trimethoprim. The findings assist to understand the level of contamination of pathogenic and MDR bacteria in raw salad vegetables, which will create awareness of food safety and public health.

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1. INTRODUCTION

Eating a diet rich in vegetables provides a lot of health-promoting benefits of the presence of different vitamins, minerals, fiber, and other bioactive agents in vegetables (Asaduzzaman and Asao, 2018; Liu, 2013; Samtiya et al., 2021; Slavin and Lloyd, 2012). Many worldwide public health campaigns have also been engaged to promote the health benefits of vegetables. As a result, the consumption of vegetables is on the rise nowadays. Even though, in many countries, the intake of vegetables is below recommended levels (Frank et al., 2019; Moura and Vialta, 2022). Again, research suggests that daily intake of raw vegetables as salad boosts up the health factor significantly as they have non-labile nutrients (Brookie et al., 2018).

However, the consumption of raw vegetables has been the cause of great public health concern as they may be contaminated with a wide variety of pathogenic microorganisms in so many ways (Amaechi et al., 2016; Cardamone et al., 2015; Chau et al., 2014; IU et al., 2015; Mohamed et al., 2016; Tefera et al., 2014). Several recent studies have reported the contamination of raw vegetables that harbor the pathogenic bacteria and parasites, e.g., *Salmonella*, *Shigella*, *Escherichia coli* (*E. coli*), *Clostridium*, *Staphylococcus*, *Campylobacter*, *Vibrio*, etc., which cause foodborne illness (Akoachere et al., 2018; Cruz et al., 2019; Luna-Guevara et al., 2019).

Dhaka city has been booming with restaurants and catering services for the past few years. According to a daily
newspaper “The Financial Express” published on 22nd February 2023, Dhaka city has over ten thousand restaurants and the numbers are increasing day by day. The variety of cuisines is diverse that covers many continents of the world. Furthermore, people are fond of going outside to eat at restaurants very often. While dining at a restaurant, most commonly salads are served as a side dish which usually contains a mixture of raw vegetables, e.g., cucumbers, onions, green chilis, lemons etc. (Rahman and Noor, 2012). However, good hygiene practice varies in different restaurants in different areas of the city. Restaurants in areas that contain high-class society maintain good hygiene practices, but such practice is rare in areas that contain a mixed class of people. In this area, the chances of contamination of raw salad vegetables with bacterial pathogens are high. Accordingly, an individual is more prone to be infected by different pathogens in the aforesaid type of unhygienic restaurants (Alam et al., 2017; Nizame et al., 2019).

Foodborne illnesses with microbial origins are very common in Bangladesh. Approximately, 30 million people suffer from foodborne illnesses such as diarrheal diseases, which are the most common food poisoning cases in Bangladesh, every year (Noor and Feroz, 2016). Pathogens such as *Escherichia coli*, *Salmonella*, *Klebsiella*, *Shigella*, etc. are transmitted by food such as raw meat and vegetables. These species are well known to originate foodborne diseases that can cause serious health issues such as diarrhea, stomach infection, kidney failure, and in some cases, death (Khairuzzaman et al., 2014). Additionally, MDR microorganisms have made the food safety situation more vulnerable in public health in Bangladesh (Ali et al., 2011). It might very well be that raw salad vegetables are also contaminated by MDR bacteria. A study has also reported that vegetables, crops etc. grown using manure as fertilizer, have shown the contamination of bacteria such as *Escherichia coli* O157:H7, *Salmonella*, *Klebsiella* spp., etc., which may act as very prominent MDR bacteria (Feroz et al., 2013; Rahman and Noor, 2012).

In the present study, we aim to determine the pathogenic and MDR bacteria from raw salad vegetables served at different restaurants located in Mirpur, Dhanmondi, Old Dhaka, Gulshan, and Bashundhara Residential Area of Dhaka city.

2. MATERIALS AND METHODS

A. Sample Collection and Processing

Fifty different samples of common raw salad vegetables like cucumbers, carrots, radishes, cabbages, green chilis, and coriander leaves in cut or grated form were collected from different restaurants in Dhaka city. Each sample was placed in a sterile Ziplock bag and subsequently transported to the laboratory in a sampling box with ice packs maintaining a temperature of 4 to 6°C. Samples were then weighed while being sealed in the Ziplock bag. 50 g of Ringer’s solution was then added to 25g of the raw salad vegetables in the Ziplock bag (ratio of Ringer’s solution and raw salad vegetable; weight/weight = 2:1) and mixed thoroughly by using a vortex mixer. Then, 50 µl of the sample was taken from the Ziplock bag and placed on a MacConkey agar plate to determine gram-negative and enteric bacteria. The rest of the sample in the Ziplock bag was passed through a membrane filter (pore size 0.2 µm) and subsequently the filter was put on an mFC agar plate for the detection and enumeration of fecal coliforms.

B. Microbiological Analyses

All media were prepared according to the manufacturer’s protocol. Media used for bacterial growth, isolation, and maintenance were MacConkey agar (Oxoid Ltd., Basingstoke, Hampshire, England), mFC agar (Sigma Aldrich, Germany), *Salmonella*-Shigella (SS) agar (Techno Pharmchem, India), Eosin-Methylene Blue (EMB) agar (Oxoid Ltd., Basingstoke, Hampshire, England). After incubation of the mFC agar plates at 37°C for 18-22 hours, it showed characteristic blue colonies which were counted as total coliform bacteria. Fecal coliforms were counted by incubating another set of inoculated mFC agar plates at 44.5°C (Cappuccino and Sherman, 1996).

MacConkey agar plate was used to detect *Escherichia coli*. However, *Salmonella* could also be cultured on this media and detected through colourless and transparent colonies. A single colony from the MacConkey subculture plate is taken with the help of a sterile inoculation loop. The loop is then swabbed on the EMB agar plate and kept at 37 °C for 24 hours in an incubator. EMB agar plates were used here to identify *E. coli*. Colourless and transparent colonies grown on MacConkey agar plates were selected for sub-culture on SS agar, which was conducted and inoculated by using an inoculation loop. SS agar plates were used here to identify *Salmonella* spp.

C. Antibiotic Sensitivity Test

In order to determine the sensitivity of *Salmonella* spp., a panel of antibiotics with their respective concentrations was used (Jorgensen and Pfaller, 2015). A portion of the fresh culture of *Salmonella* isolates was used to prepare 0.5 Macferland standard concentration of cell suspension which was then spread onto Mueller Hinton agar (Himedia Ltd., India) and dried for 15 minutes. A total of 11 types of antibiotics amoxicillin (25 µg), ampicillin (10 µg), azithromycin (15 µg), chloramphenicol (30 µg), ciprofloxacin (5 µg), erythromycin (15 µg), kanamycin (30 µg), norfloxacin (10 µg), streptomycin (10 µg), tetracycline (30 µg), and trimethoprim (5µg) discs were placed onto Mueller Hinton agar following standard procedure, plates were then incubated at 37 °C for 18-20 hours. The zone diameters were measured after incubation to determine their sensitivity and resistance against the tested antibiotics.

The inoculation loop used previously for the sub-culture of SS agar plates was streaked on the nutrient agar inside the vial tube and sealed to prevent any contamination of other species. The samples were then stored for biochemical and polymerase chain reaction (PCR) tests. Major biochemical tests such as Kligler’s Iron Agar (KIA), Motility indole urease (MIU), Methyl-Red (MR), Voges-Proskauer (VP), citrate utilization and oxidase tests were carried out according to the standard methods (Alfrad, 2007; Cappuccino and Sherman, 1996).
D. Detection of Salmonella spp. by PCR
Isolated colonies of *Salmonella* spp. were used for molecular detection of the STM 3098 gene by PCR method (Kim *et al.*, 2006). A portion of a fresh colony of biochemically identified cells was dislodged in an Eppendorf tube in 1 ml sterile DNase and RNase-free water and boiled for 10 minutes. Samples were then centrifuged at 10000 rpm for 5 minutes and a DNA template was collected from the supernatant. A 50 μl PCR mixture contained 5 μl of DNA template, 1 μl (100 pmol) of each primer and a 25 μl of Taq PCR Master Mix polymerase containing 100 mM Tris-HCl, 500 mM KCl at pH 8.3 at 20 °C, 1.5 mM MgCl₂, 200 M each deoxyribonucleoside triphosphate and 0.025 U Taq polymerase (Qiagen, USA). Amplification of DNA was performed using Mastercycler® personal (Eppendorf, USA) PCR machine. Heat denaturation was performed at 95 °C for 5 minutes, followed by 35 cycles (90 s at 95 °C, 60 s at 62 °C, and 90 s at 72 °C) and an elongation step of 7 minutes at 72 °C. The primers used were STM 3098 F (5’-TTTG CGCGC GAGTG ATTC-3’) and STM R (5’-GCTT CCGCC CATCA ATCCG-3’), which amplified a 423-bp fragment of *Salmonella* spp. specific genes, as shown in Figure 1.

3. RESULTS
A. Incidence of Coliforms and Fecal Coliforms in the Study Area
The lowest and the highest total coliform counts were obtained from the samples of Dhanmondi (i.e., 4.0 × 10¹ cfu/ml) and Old Dhaka (i.e., 4.02 × 10¹ cfu/ml), respectively, as shown in Table 1. The highest fecal coliform count was also obtained from the samples of Old Dhaka (i.e., 1.2 × 10¹ cfu/ml), as shown in Figure 2. In both cases, the highest average counts of organisms were found in Old Dhaka, as shown in Figure 2.

B. Presence of Salmonella spp. and E. coli in the Studied Samples
Salmonella spp. considered as very common food pathogens, were identified in the raw salad vegetable samples by plating them onto MacConkey agar. Additionally, *E. coli* and *Salmonella* spp. colonies were verified by sub-culturing on EMB and SS agar, respectively. However, the presence of *E. coli* and *Salmonella* colonies was found only in the samples collected from old Dhaka, Mirpur and Bashundhara R/A.

C. Identification and Further Confirmation of the Genera of the Selected Salmonella Species from the SS Plates
For the biochemical test, six isolates from the nine attributed *Salmonella* spp. based on their MDR test were selected for further characterization and identification. Among the selected six, one isolate was from Mirpur, four from Old Dhaka and one was from Bashundhara R/A. Biochemical test results of the samples shown in Table 2 suggested further confirmations of the genera of the selected *Salmonella* spp.

D. PCR Detection of Salmonella spp.
The result showed that out of five areas, three showed the presence of *Salmonella* spp. by culture technique which was further confirmed by PCR method. Figure 1 shows the PCR amplicons of the STM 3098 gene. *Salmonella* spp. were detected in samples collected from Mirpur (S-10), Old Dhaka (S-1, S-6, S-7, S-8) and Bashundhara R/A (S-3).

E. Antibiotic Resistance of Salmonella spp.
According to the morphological characteristics of the culture medium (SS plates), nine samples were attributed as *Salmonella* spp. and considered for antibiotics sensitivity test (Wayne, 2020). Among the nine isolates, three were from Mirpur, five from Old Dhaka and one from Bashundhara R/A. All *Salmonella* spp. were resistant to trimethoprim. Additionally, a few of the isolates were resistant to amoxicillin, ampicillin, erythromycin and chloramphenicol (Table 3).

Figure 1: PCR detection of STM 3098 gene of *Salmonella* spp. after electrophoresis on 2% agarose gel. Lane M, 100bp DNA ladder, Lane 1, Negative control; 2, 3, 4 (S1, S6, S7), 7, 10, 11 (S8, S10, S3) show positive result for STM 3098 gene (423bp)
Table 1
Microbial load in raw salad vegetable samples collected from restaurants in different locations in Dhaka city

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Mirpur (poor hygiene)</th>
<th>Dhanmondi (moderate hygiene)</th>
<th>Old Dhaka (poor hygiene)</th>
<th>Gulshan (Good hygiene)</th>
<th>Bashundhara R/A (Good hygiene)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TC (cfu/ml)</td>
<td>FC (cfu/ml)</td>
<td>TC (cfu/ml)</td>
<td>FC (cfu/ml)</td>
<td>TC (cfu/ml)</td>
</tr>
<tr>
<td>S-1</td>
<td>2.4×10^2</td>
<td>4.0×10^1</td>
<td>1.12×10^3</td>
<td>6.0×10^1</td>
<td>3.5×10^3</td>
</tr>
<tr>
<td>S-2</td>
<td>2.0×10^2</td>
<td>6.0×10^1</td>
<td>4.0×10^1</td>
<td>0</td>
<td>1.1×10^3</td>
</tr>
<tr>
<td>S-3</td>
<td>1.3×10^3</td>
<td>1.6×10^2</td>
<td>8.0×10^1</td>
<td>0</td>
<td>1.8×10^2</td>
</tr>
<tr>
<td>S-4</td>
<td>2.7×10^3</td>
<td>2.8×10^2</td>
<td>1.2×10^3</td>
<td>0</td>
<td>2.7×10^3</td>
</tr>
<tr>
<td>S-5</td>
<td>3.0×10^3</td>
<td>1.2×10^3</td>
<td>1.6×10^3</td>
<td>8.0×10^1</td>
<td>1.26×10^3</td>
</tr>
<tr>
<td>S-6</td>
<td>3.5×10^3</td>
<td>2.4×10^3</td>
<td>3.2×10^3</td>
<td>8.0×10^1</td>
<td>3.0×10^3</td>
</tr>
<tr>
<td>S-7</td>
<td>1.0×10^3</td>
<td>6.0×10^1</td>
<td>2.0×10^2</td>
<td>0</td>
<td>2.5×10^3</td>
</tr>
<tr>
<td>S-8</td>
<td>2.6×10^3</td>
<td>3.2×10^2</td>
<td>1.0×10^3</td>
<td>4.0×10^1</td>
<td>4.0×10^3</td>
</tr>
<tr>
<td>S-9</td>
<td>1.2×10^3</td>
<td>2.0×10^1</td>
<td>7.4×10^2</td>
<td>2.0×10^1</td>
<td>5.4×10^2</td>
</tr>
<tr>
<td>S-10</td>
<td>3.8×10^3</td>
<td>4.0×10^2</td>
<td>8.0×10^2</td>
<td>6.0×10^1</td>
<td>3.7×10^3</td>
</tr>
</tbody>
</table>

Legend: TC – total coliform, FC – fecal coliform, R/A – residential area

Figure 2: Total coliforms and fecal coliforms distribution in raw salad vegetables
Sarker et al.:
Prevalence of Multidrug-Resistant Salmonella in Raw Salad Vegetables in Dhaka Metropolitan Area

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Table 2
Results of biochemical tests of the pathogenic isolates

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Locations</th>
<th>KIA</th>
<th>MIU</th>
<th>MR</th>
<th>VP</th>
<th>Citrate</th>
<th>Oxidase</th>
<th>Identified organisms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-10</td>
<td>Mirpur</td>
<td>K</td>
<td>A</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>S-1</td>
<td>Old Dhaka</td>
<td>K</td>
<td>A</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>S-6</td>
<td>Old Dhaka</td>
<td>K</td>
<td>A</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>S-7</td>
<td>Old Dhaka</td>
<td>K</td>
<td>A</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>S-8</td>
<td>Bashundhara R/A</td>
<td>K</td>
<td>A</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>S-3</td>
<td>Bashundhara R/A</td>
<td>K</td>
<td>A</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Legend: V = 10-80% positive, K = alkaline, A = acidic, + = positive result, - = negative result, +/- = undefined result

Table 3
Antibiotic sensitivity pattern of the selected Salmonella spp.

<table>
<thead>
<tr>
<th>Antibiotics</th>
<th>Diameter of zone inhibition standard (mm)</th>
<th>Sensitivity pattern of isolates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Resistant</td>
<td>Intermediate</td>
</tr>
<tr>
<td></td>
<td>≤</td>
<td>≥</td>
</tr>
<tr>
<td>Amoxicillin</td>
<td>13</td>
<td>14-17</td>
</tr>
<tr>
<td>Ampicillin</td>
<td>13</td>
<td>14-16</td>
</tr>
<tr>
<td>Azithromycin</td>
<td>13</td>
<td>14-17</td>
</tr>
<tr>
<td>Chloramphenicol</td>
<td>12</td>
<td>13-17</td>
</tr>
<tr>
<td>Ciprofloxacin</td>
<td>15</td>
<td>16-20</td>
</tr>
<tr>
<td>Erythromycin</td>
<td>13</td>
<td>14-22</td>
</tr>
<tr>
<td>Kanamycin</td>
<td>13</td>
<td>14-17</td>
</tr>
<tr>
<td>Streptomycin</td>
<td>11</td>
<td>12-14</td>
</tr>
<tr>
<td>Tetracycline</td>
<td>11</td>
<td>12-14</td>
</tr>
<tr>
<td>Norfloxacin</td>
<td>12</td>
<td>13-16</td>
</tr>
<tr>
<td>Trimethoprim</td>
<td>10</td>
<td>13-16</td>
</tr>
</tbody>
</table>

Legend: S – susceptible, R – resistance, I – intermediate

4. DISCUSSION
In the present study, total coliform counts were performed for all the samples and all of them showed the existence of coliform, while fecal coliforms were detected in most of them on mFC agar medium. But the salad samples collected from the Old Dhaka region were more contaminated with fecal coliforms and Salmonella spp. than that of other regions. The plausible cause might be the high population density and unhygienic practices in Old Dhaka. Too many people with overcrowded housing have generally steered the environment to an unhealthy state (Bangladesh Bureau of Statistics, 2012). Additionally, the staffs of the restaurants are often uneducated and they do not have adequate knowledge of safe food handling. Furthermore, unhygienic sanitation and contaminated drinking water supply made the situation more critical (Hasan et al., 2019). Thus, dense population and improper management are the determinant factors for the highest count of bacteria in Old Dhaka. The second region is Mirpur where low- and middle-income groups live in, and the hygienic condition is also worse than in other study areas except for Old Dhaka (Akhie and Ahmed, 2018). The
third contaminated raw salad vegetable was found in Bashundhara R/A where three universities are located and more than thirty thousand students live in this area. Therefore, one of the significant factors influencing the quality of restaurants in this area is obviously to cater cheaper priced foods to students. Consequently, the restaurants are also more focused on their sales and profits rather than hygiene. On the other hand, Gulshan and Dhanmondi areas are fairly better as people of high income can afford to live there (Kamruzzaman & Ogura, 2007; Satu & Chiu, 2019). Hence, restaurants following different hygienic processes with different price ranges were explored in Dhaka city during this study. Only Salmonella spp. isolated from collected raw salad vegetables were considered for antibiotic sensitivity tests in our study as shown in Table 3. When isolates showed resistance against more than one antibiotic were considered to be multidrug-resistant (MDR) bacteria. In this study, MDR Salmonella spp. was more prevalent in Old Dhaka. Presently, it has been considered to be a menace to public health all over the world at an alarming rate (Rozario et al., 2019; Tanwar et al., 2014). Numerous studies also reported a significant number of MDR contaminating bacteria in raw salad vegetables, e.g., carrot, lettuce, cucumber, tomato, chili, onion, capsicum, and coriander (Alam et al., 2015; Noor et al., 2015; Rahman and Noor, 2012). The contamination and development of these MDR bacteria in these freshly produced salads have emerged due to the inappropriate use of antimicrobial drugs, maintaining poor hygiene, improper food handling etc.

5. CONCLUSIONS

The consumption of raw salad vegetables in restaurants with poor hygiene has emerged to the proliferation of food-borne pathogens. MDR in microbes is also spreading throughout Dhaka city. Dwellers are at a risk to be exposed to MDR pathogens through a variety of routes including food, food chain, contaminated water, unhygienic environment, etc. However, raw salad is an important route of possible MDR infection as raw salad intake is a common practice in restaurants in Dhaka city. Raw salad preparation, washing and poor hygiene knowledge of the restaurant workers have led to a potential threat to public health. Necessary steps should be taken to remove the pathogens from the raw salad preparation in restaurants. Food handlers should also be trained in food safety, which alternatively ensures the safety of the consumers.

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REFERENCES


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