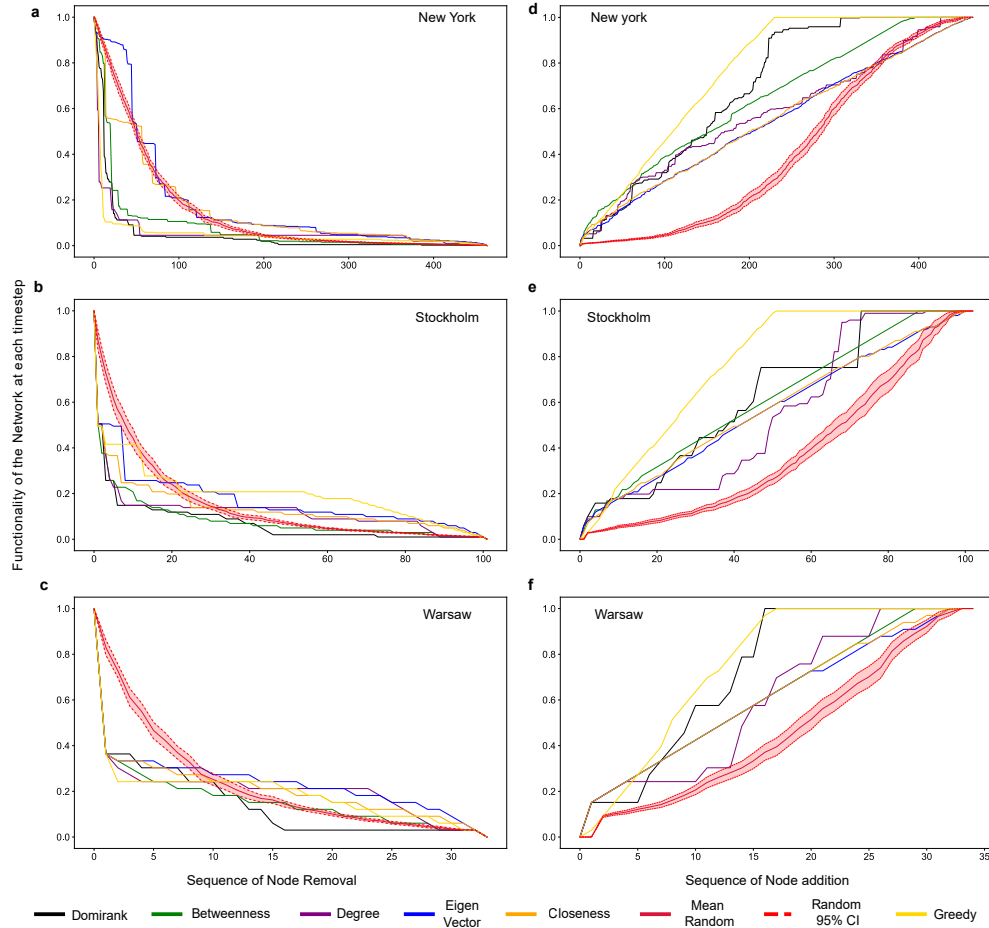
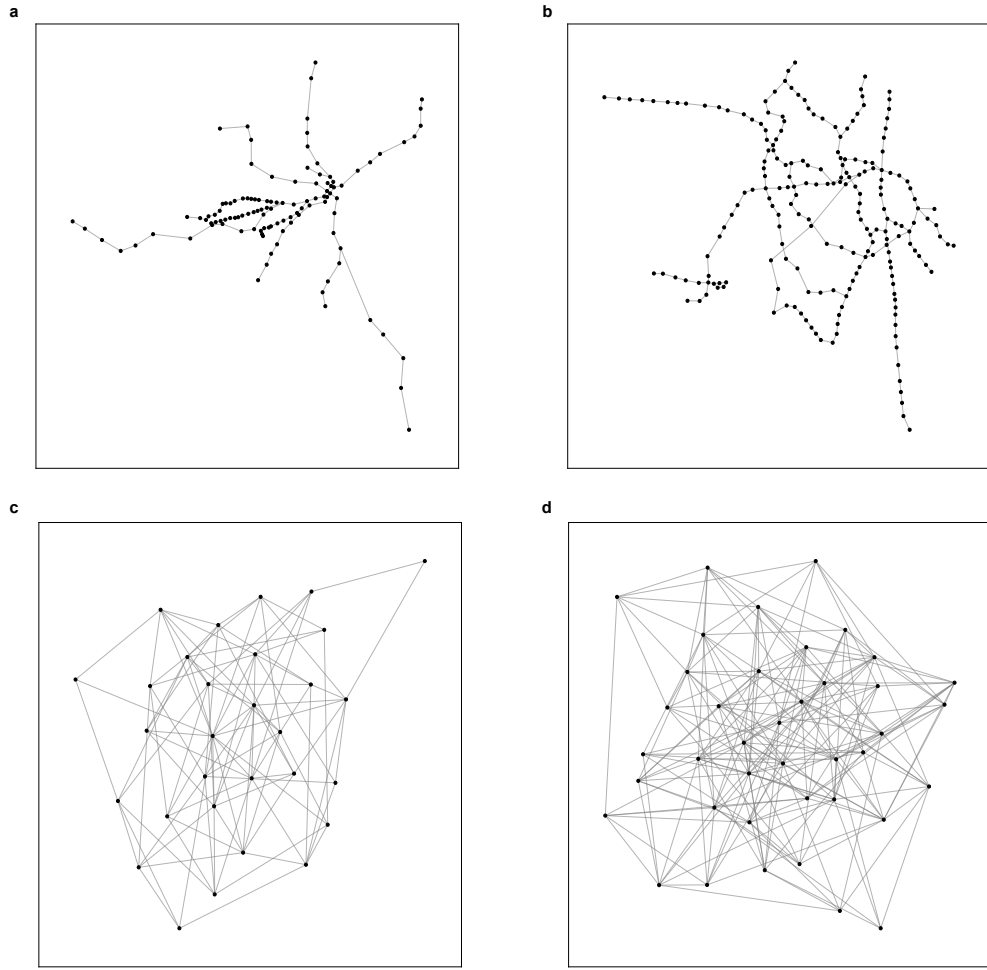


Supplementary Material

Supplementary Figures



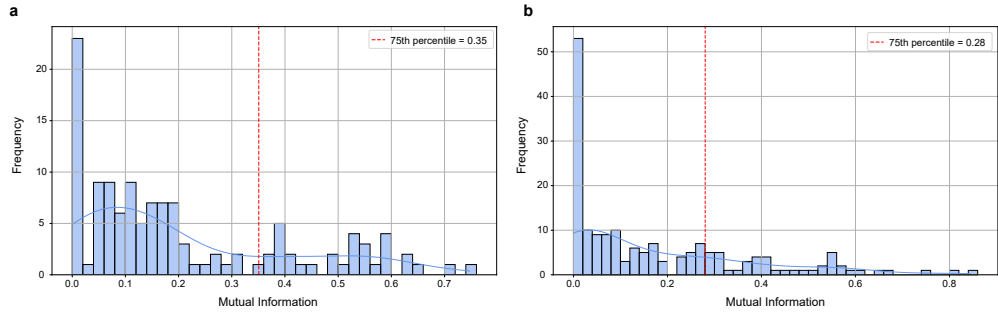
Supplementary Figure 1 Resilience performance curves under node failure and recovery strategies. Panels (a–c) show how the network functionality degrades with sequential node removals across three cities of varying scale New York (large), Stockholm (medium), and Warsaw (small). Panels (d–f) illustrate the corresponding recovery sequences, where nodes are reintroduced in different orders. Each line represents a distinct strategy, centrality based (Domirank, Betweenness, Degree, Eigenvector), Mean Random and Greedy attacks and recovery. These patterns emphasize the varying impacts of sequence of node removal on both fragility and restoration potential across urban metro rail systems. The red dashed line denotes the average performance of 50 random simulations, with the surrounding shaded band indicating the 95% confidence interval. These examples highlight how resilience trajectories vary by both strategy and underlying network structure.



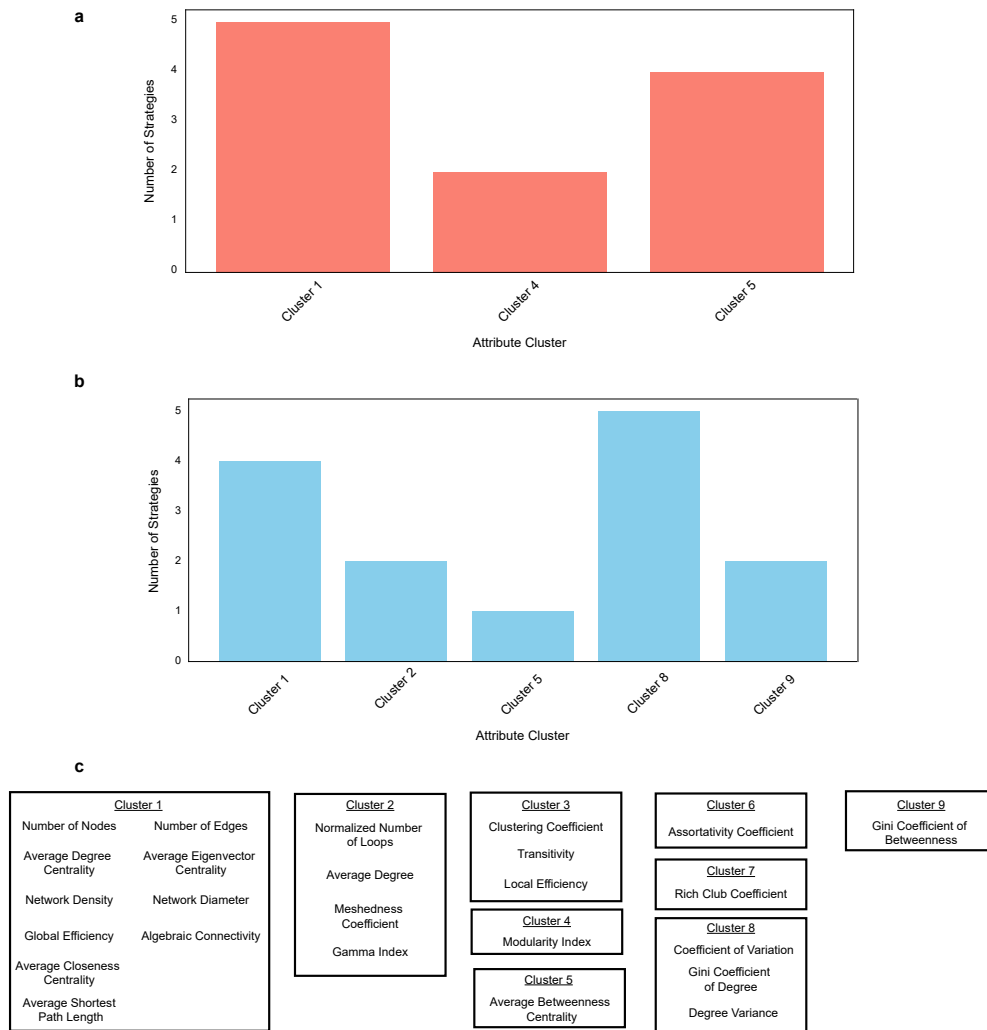
Supplementary Figure 2 Real World vs. Synthetic High Density Urban Metro Rail Networks. (a) Boston and (b) Delhi metro networks visualized using geospatial coordinates to reflect their true layout and branching topology. (c) and (d) show two synthetic, densely connected graphs generated using the Erdős-Rényi model.



Supplementary Figure 3 Mutual information heat map of topology attributes versus failure AUC including Eigenvector and Closeness based strategies. Mutual information between 25 structural attributes and AUC scores for all failure strategies including the Eigenvector and Closeness guided failures. Virtually all scores in these two columns fall below 0.20 (deep red), indicating negligible explanatory power compared with the other five strategies. Owing to this consistently low signal, Eigenvector and Closeness based failures were excluded from the main comparative analysis.



Supplementary Figure 4 Distributions of mutual information scores and selection threshold for high mutual information attributes. (a) Distribution of mutual information values between topology attributes and failure AUC. The red dashed line marks the 75th percentile threshold (mutual information=0.35); only attributes to the right of this cutoff are retained as failure relevant. (b) Distribution of mutual information values for recovery AUC. The 75th percentile cutoff (mutual information = 0.28) isolates the top quartile of information rich attributes used in the recovery analysis.



Supplementary Figure 5 Frequency of attribute cluster occurrence above the high mutual information threshold across failure and recovery strategies (a) Failure strategies ($n = 5$). Bars show, for each attribute cluster, the number of failure strategies in which the cluster appears at least once above the 75th percentile mutual information threshold. (b) Recovery strategies ($n = 7$). Bars show, for each attribute cluster, the number of recovery strategies in which the cluster appears at least once above the 75th percentile mutual information threshold. (c) Cluster definitions showing which network attributes belong to each cluster.

Supplementary Tables

Supplementary Table 1 Network attributes used across resilience studies in urban rail transit networks. Each "✓" indicates the attribute is used in the corresponding study.

Attributes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Number of Nodes					✓					✓					✓		✓	✓	✓	✓	
Number of Edges					✓					✓					✓		✓	✓	✓	✓	
Average Degree	✓									✓	✓		✓			✓	✓	✓	✓	✓	✓
Average Shortest Path Length	✓			✓	✓		✓		✓	✓		✓	✓		✓	✓	✓	✓			✓
Network Diameter			✓	✓		✓	✓				✓	✓		✓	✓			✓			
Network Density				✓																	✓
Clustering Coefficient		✓				✓		✓	✓				✓	✓		✓				✓	
Modularity Index										✓											
Global Efficiency	✓	✓											✓	✓		✓	✓		✓		
Normalized Number of Loops			✓							✓											
Average Degree Centrality			✓			✓			✓		✓	✓	✓							✓	
Average Betweenness Centrality	✓		✓	✓		✓		✓		✓	✓	✓	✓		✓	✓		✓			
Average Closeness Centrality			✓			✓															✓
Average Eigenvector Centrality			✓			✓					✓						✓				✓
Assortativity Coefficient			✓	✓																	
Local Efficiency					✓																
Meshedness Coefficient				✓																✓	
Gini Coefficient of Degree																					✓
Gini Coefficient of Betweenness																					✓
Gamma Index																					✓
Rich Club Coefficient																					✓
Algebraic Connectivity																					
Transitivity																					
Coefficient of Variation																					
Degree Variance																					

Supplementary Table 2 Presence of high-mutual-information clusters for **failure** and **recovery** strategies. An “✓” marks each attribute cluster that appears above the 75th-percentile MI threshold for the given strategy.

Strategies	C1	C2	C3	C4	C5	C6	C7	C8	C9
Domirank Failure	✓			✓	✓				
Betweenness Failure	✓			✓	✓				
Degree Failure	✓				✓				
Mean Random Failure	✓								
Greedy Failure	✓				✓				
Domirank Recovery		✓						✓	✓
Betweenness Recovery								✓	✓
Degree Recovery								✓	
Eigenvector Recovery	✓								
Closeness Recovery	✓								
Mean Random Recovery	✓							✓	
Greedy Recovery	✓	✓			✓			✓	