A novel hybrid approach for alignment modelling of virtual trial assembly of steel box girder bridge

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Abstract

Inspecting completed steel box girder bridges is a standard requirement. Before construction, the steel box girder is pre-assembled to ensure its alignment meets construction requirements. However, current inspection processes still largely rely on manual labour and are subject to the expertise of engineers. This paper presents a hybrid modelling approach that combines geometric and statistical methods to predict the bridge shape in the Virtual Trial Assembly (VTA) process using extracted corner points from great amount point cloud data. Results from a case study show that this hybrid modelling approach can accurately and efficiently extract the corner points from steel box girders and model the bridge alignment in VTA with maximum deviation of 1.6mm for more than 90% of point data and 1.4 mm for corner points, while requiring less data collection and modelling time. This method provides a more accurate and effective solution for arch ribs inspection and line shape prediction of steel box girder bridges, accelerating construction progress and improving construction quality.

1. Introduction

Prefabricated structures are popular in AEC due to their environmental adaptability, but prefabricated components must be manufactured with precise tolerances to avoid installation issues and rework. Physical trial assembly (PTA) is a complex, inefficient, and costly method to detect manufacturing deviations in prefabricated components, limited by site space for large components (Case et al., 2014). Virtual trial assembly (VTA), a digital pre-assembly method, is more efficient, cost-effective, and free of space limitation, increasingly used in steel box girder bridge construction (Xu-hong et al., 2021). In the VTA process for steel box girder bridges, the end corner points are often used as key inspection control points to determine the bridge alignment. The identification and extraction of corner points and the prediction of the bridge alignment are crucial for the VTA process.

Laefer and Truong-Hong (2017) and Yang et al. (2020) proposed methods for matching point clouds to design models by using point identification extraction algorithms. Liu (2022) has proposed a direct fit method for extracting corner points, which however cannot solve the problem of extracting corner points at the end of steel box girders that are intersected by planes. In a related study on shape prediction for pre-assembly, Case et al. (2014) used the generalised Pratt's algorithm to achieve matching between points, while Maset et al. (2019) used the same algorithm to match welded counterparts. However, these two studies only consider the optimum splicing distance between the identified features within a given target value range and are not applicable for predicting the alignment of steel box girder bridges.

This paper proposes a novel approach to extract and model corners of steel box girder components of bridges for accurate alignment modelling and prediction in VTA. It combines geometric and statistical methods to predict the shape of the bridge during the Virtual Trial Assembly (VTA) process. By utilizing point cloud data and extracting corner points, the proposed approach aims to improve the accuracy and reliability of the inspection process, which has traditionally relied on manual labour and expert knowledge.

2. Methodology

This study proposes a three-stage methodology for precise corner point extraction and virtual trial assembly technology for steel box girders in bridge construction (Figure 1). The first stage involves data pre-processing, which includes point cloud denoising and segmentation to reduce noise and facilitate data processing and analysis. Point cloud denoising eliminates any outliers, while segmentation divides the data into smaller regions. In the second stage, the extraction and modelling of the steel box girder corner points is crucial for detecting and aligning the girder after virtual trial assembly. The corner points are located at the end connections of the girder. Finally, virtual trial assembly technologies and design CAD drawings are employed to forecast the bridge alignment, aiding in the accurate assembly of the steel box girder and providing additional information for more precise assembly. This proposed hybrid methodology effectively combines data pre-processing, point cloud analysis, and virtual trial assembly technologies to enhance the accuracy and efficiency of steel box girder assembly in bridge construction, ultimately resulting in reduced construction time and costs.

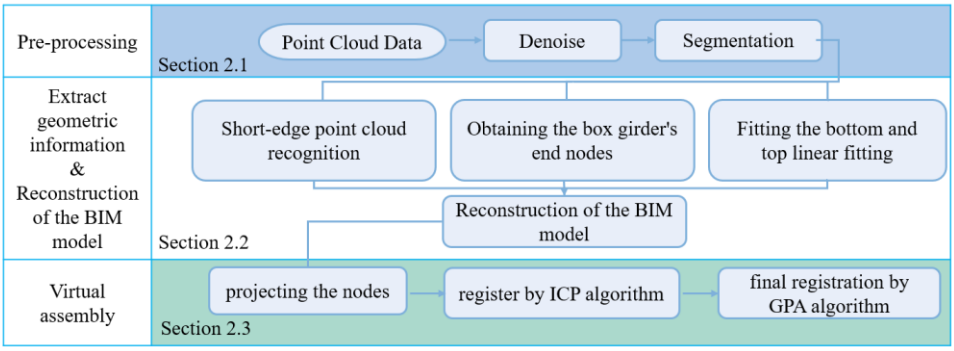


Figure 1: Overview of the proposed method for the novel hybrid approach

2.1 Pre-processing

The pre-processing of steel box girder point cloud data is crucial to ensure the accuracy and effectiveness of subsequent virtual trial assembly processes. A two-step approach involving point cloud denoising and segmentation is used to achieve this. While point cloud denoising removes any outliers and reduces noise, the effectiveness of point cloud segmentation, which divides the data into smaller regions, directly determines the processing outcome of the subsequent data analysis. Therefore, optimising the point cloud segmentation method is a critical research focus in this section, as it can significantly impact the accuracy and efficiency of virtual trial assembly for steel box girder construction.

2.1.1 Denoising

Point cloud data obtained from steel box girders may contain noise that can negatively impact subsequent processing due to environmental and instrument factors. Therefore, it is essential to perform denoising on the point cloud data. The normal-based bilateral filtering algorithm is a well-established method for reducing noise as it considers both the distance from neighbouring points to the point and the distance along the normal direction. This approach preserves sharp edges better and performs well in filtering noise while retaining important features. Therefore, this paper uses normal-based bilateral filtering to reduce the noise of the steel box girder point cloud.

2.1.2 Segmentation

Point cloud segmentation aims to identify the point clouds belonging to the real sides and the base flange of the steel box girders s, which are used as the fundamental source of steel box girder corner points data. The protruding part of the side of a steel box girder creates a diffraction effect on the point cloud, making it difficult to identify the real side and ground point clouds. While the growth algorithm based on normal vectors is widely used for identifying point clouds, such algorithms and their derivatives rarely focus on diffraction point cloud segmentation. Therefore, this study develops an adapted-growth algorithm based on normal vectors, which can provide an accurate normal vector growth threshold, enabling quick and stable identification of the point cloud with diffraction in steel box girders.

The newly developed adapted-growth algorithm operates based on four parameters (r_1, r_2 , $min\theta_1$and $max\theta_2$), upon which four fundamental concepts (namely seed point, neighbourhood point, normal vector, and seed sequence) are built on. The method involves finding the neighbour points of each point in the point set, i.e., the points within the range of $\mathrm{r}_1$from the seed point. The points in this range are fitted, and their normal vectors are obtained and used as the normal vector of the point. A point from the point set is then taken as a seed point, and its search radius $\mathrm{r}_2$is searched for, i.e., points within the range of r_2 from the seed point are determined. It is then determined whether the normal vectors of these points are in the interval $[\theta_1\ \theta_2]$, and the neighbourhood points meeting the conditions are added to the seed sequence while being deleted from the point set. The growing process continues until no neighbour point satisfying the condition can be found.

As the side point cloud exhibits a planar feature, the minimum angle threshold of the growing algorithm is set to 0°. The key factor in determining the maximum angle threshold of the growth algorithm is how it affects the segmentation of the point cloud. In this regard, the maximum angle threshold is determined by two factors, (1) calculating the maximum transformation angle $\theta_1$of adjacent points based on the arch axis formula, and (2) determining the angle θ_2 between the diffraction plane of the point cloud and the plane of the steel box girder.

The maximum transformation angle $\theta_1$of adjacent points calculated by the arch axis formula,

$$\max(|Norm(x_{i+1}) - Norm(x_i)|) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2-1)$$

where x_{i+1} and x_i are the adjacent abscissas of the arch rib in the x-axis direction of the arch rib, and $Norm(x_i)$ is the normal vector of point x_i.

An arch axis is designed as a catenary, represented by:

$$y(x) = f - \frac{f}{m-1} * \left(cosh\left(K * \frac{x}{l}\right) - 1\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2-2)$$

where f is the height of the arch bridge, m is the coefficient of the arch axis, l is the arch span, and K is defined as:

$$K = log_e\left(m + \left(m * (m-1)\right)^{\frac{1}{2}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \ldots\ldots(2-3)$$

The diffraction phenomenon model of the point cloud is then analysed, and the angle θ_2 between the diffraction plane of the point cloud and the plane of the steel box girder can be obtained.

The point cloud data of a steel box girder segment are then segmented properly through the proposed algorithm with proper thresholds (Figure 2(b)). The effects of threshold values are also discussed, where Figure 2(c) shows the result obtained when the parameter threshold value is too small, resulting in over-segmentation, and the Figure 2(d) shows the result obtained when the parameter threshold value is too large, leading to under-segmentation.

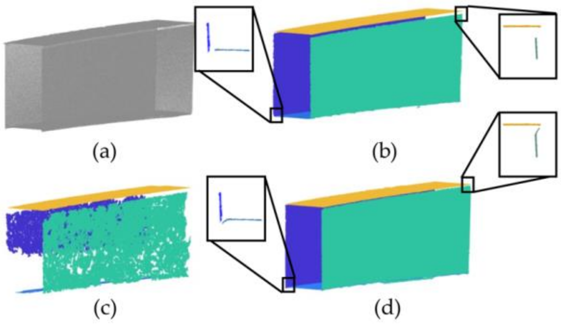


Figure 2: Point cloud segmentation effect under different angle thresholds

2.2 Extraction of geometric information

2.2.1 Short-edge point cloud recognition

The short-edge point cloud of the steel box girder port comprises the side point cloud, and the short-side point cloud of the top and bottom planes. To facilitate subsequent point cloud processing, the point cloud of the steel box girder is rotated such that the normal vector of the side point cloud is vertically oriented upward, as depicted in the Figure 3.

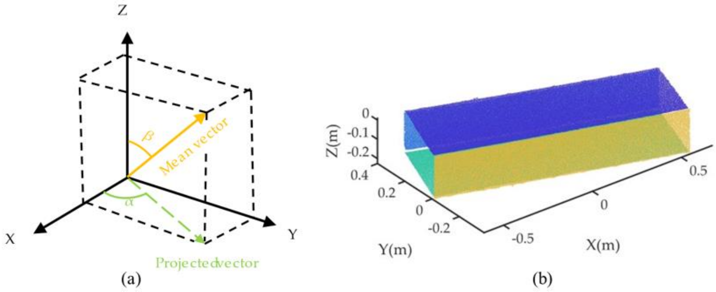


Figure 3: Depiction of rotating the point cloud

To identify the side point cloud, the two-dimensional convex hull algorithm is used to obtain the plane boundary points. The RANSAC algorithm is applied to identify the point cloud of the short edge of the side through iteratively randomly selecting two boundary points to determine a straight line until the maximum number ($N = 560$) of points.

The identification of the top and bottom short edge point clouds using the side point cloud method can be easily affected by the singularity of straight-line fitting, resulting in inaccurate identification. To overcome this challenge, a regular algorithm is developed to account for the sudden changes in the density of the boundary point clouds along the z-axis of the short sides of the top and bottom planes. The algorithm involves projecting the surface laser scanning data (LSD) onto the X-Z or Y-Z plane and obtaining the boundary points using a 2D convex wrapping algorithm. The boundary points with abrupt density changes on the z-axis are removed, and the remaining points are considered as the short edge point clouds of the top and bottom planes.

2.2.2 Obtaining the box girder's end nodes

A spatially intersection algorithm has been developed to obtain the end nodes of a steel box girder (Figure 4). Firstly, a corner point on the bottom plane of the steel box girder at the port is selected, and the search radius is defined as half the width of the bottom plane. Using this point as the centre and radius, the point cloud of plane 1 and plane 2 is obtained by searching within the segmented point cloud of the steel box girder obtained (Section 2.1). Next, the available side and bottom short-edge point clouds obtained (Section 2.2.1) are also searched using the same method, which can be used for plane 3 fitting. Finally, the intersection of the three obtained planes is solved using a face-to-face intersection algorithm, which is a reliable method for solving spatial intersections of three non-parallel faces. The proposed algorithm provides an effective approach for accurately identifying the end nodes of a steel box girder.

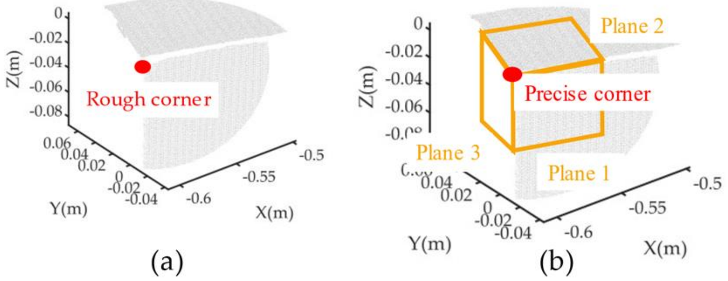


Figure 4: Solution of box girder end nodes (a) original box girder end nodes (b) three non-parallel sides

2.2.3 Linear fitting top and bottom planes

The accurate linear fitting of top and bottom planes is crucial for determining the overall linear shape of the steel box girder bridge and supporting subsequent trial assembly. Although the point clouds of the top and bottom planes are projected onto the X-Y plane for linear fitting, a few noise points close to the steel box girder planes still exist, as shown in Figure 5. To ensure the accuracy of the linear fitting, this study proposes the method of fitting the line shape with cubic polynomial. Firstly, a cubic polynomial is used to fit the line shape for the first time. Secondly, the distance from each point to the first fitted line shape is calculated, and the standard deviation of the distance is also computed. Thirdly, points that are more than three times the standard deviation from the mean distance are considered noise points and removed. Finally, a cubic polynomial as above is used again to fit the line shape for a more accurate linear shape of the steel box girder. This proposed quadratic fitting method provides a reliable approach for improving the accuracy of linear fitting, which is crucial for virtual trial assembly and the overall construction of the steel box girder bridge.

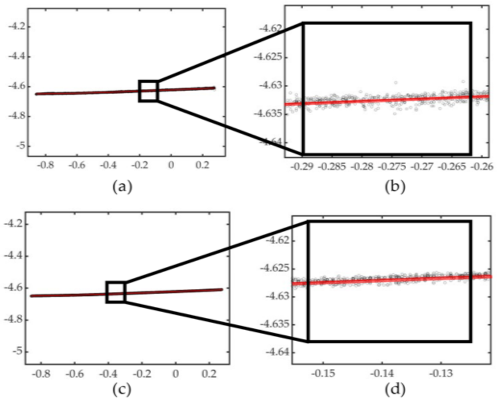


Figure 5: (a) First fitting (b) Detail of first fitting (c) Second fitting (d) Detail of second fitting

2.2.4 Reconstruction of the BIM model

The high-accuracy steel box girder model is finally constructed using Revit Dynamo, which allows the model to be parameterised and the position parameters of each node or line to be easily adjusted. The key inputs for this process are the box girder end nodes obtained from Section 2.2.2 and the bottom and top alignments from Section 2.2.3. These parameters include the 8 corner points of each steel box girder, the alignment, and the design thickness of the steel plane on each side, as shown in Figure 6.

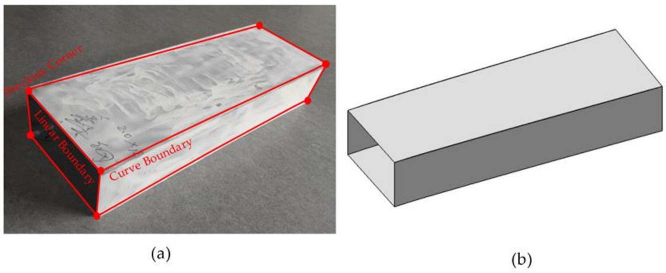


Figure 6: (a) End nodes of a box girder (b) BIM model of reverse generated steel box girder

2.3 Virtual assembly

After constructing a high-accuracy virtual model of the steel box girder, the Generalized Procrustes Algorithm (GPA), a widely used method in VTA, is used for alignment of multiple models. While previous studies have successfully applied this method to assemble multi-section prefabricated rods sequentially, cumulative errors may lead to failure in the final assembly of multi-segment members. To address this challenge, this study proposes a trial assembly method that combines design drawings, involving three key steps. Firstly, the nodes of the reverse model are projected onto the graph, as depicted in the figure. Secondly, the ICP algorithm is used to roughly register the reverse model and the design drawings. Finally, the GPA algorithm is used for the final registration of the steel box girder plane, followed by fitting the z value of one side of steel box girder to calculate the z-axis displacement value of each steel box girder, as shown in Figure 7. This method provides an excellent initial position for the trial assembly for the steel box girder, effectively avoiding the accumulation of assembly errors, and enabling a more accurate and efficient construction process.

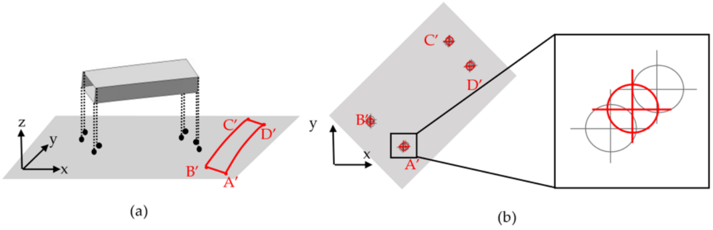


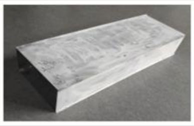
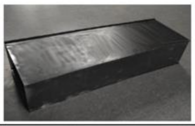
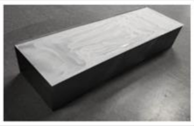
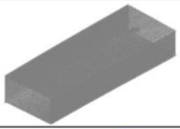
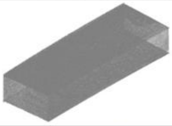
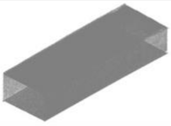
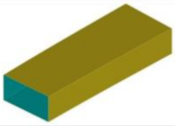
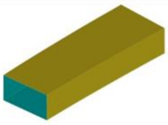
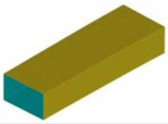
Figure 7: (a) Node projection of the model (b) Model's node projection outcome

3. Case study

3.1 Experimental Process

To examine the effectiveness and accuracy of the proposed quality assessment technique, 3-segment steel box girders were fabricated and experiments were conducted on the specimen, as shown in Table 2. The end of the specimens was a rectangle surrounded by multiple straight lines, with dimensions of 300×600mm.The purpose of the experiments was to evaluate the effectiveness and accuracy of the proposed technique in processing scan data of the specimens, comparing the point cloud with the inversion model, and assessing the accuracy of the point cloud inversion. In addition, the proposed method's trial assembly accuracy and robustness were tested on the three-section steel box girder laboratory specimens according to the assembly sequence. Finally, the accuracy of the assembly technique proposed in this paper was verified by physical trial assembly testing, as shown in Figure 8.

Table 2 Images, LSDs, and models of three scaled-down component

	Arch rib 1	Arch rib2	Arch rib3
Image			
LSD			
Model			

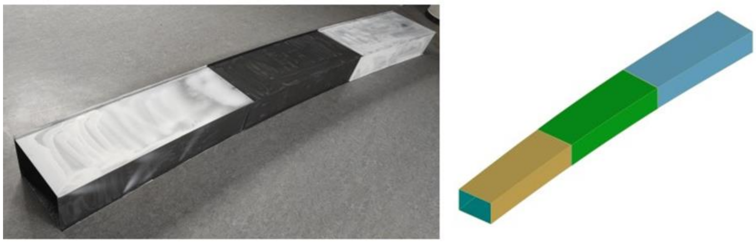

(a)
(b)

Figure 8: (a) PTA findings from the steel box girder experiment (b) VTA results from the steel box girder BIM model

3.2 Result and Discussion

The results show that the deviations between VTA model line and design line can be identified and visualised (shown in Figure 9), which provides an important indicator for quality monitoring of the VTA process of steel box girder bridge. It can further help the construction workers to assess the weld size or cut size, as shown in Figure 10.

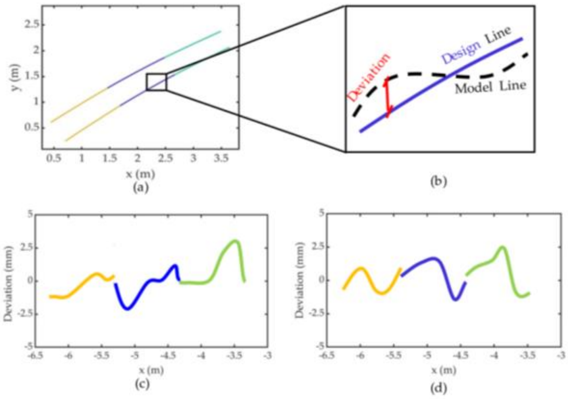


Figure 9: (a) Designed line shape of Top and Bottom planes (b) Line shape deviation between VTA and design models (c) Line shape deviation of the top plane (d) Line shape deviation of the bottom plane

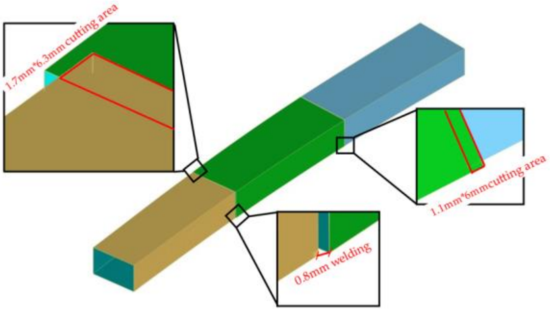
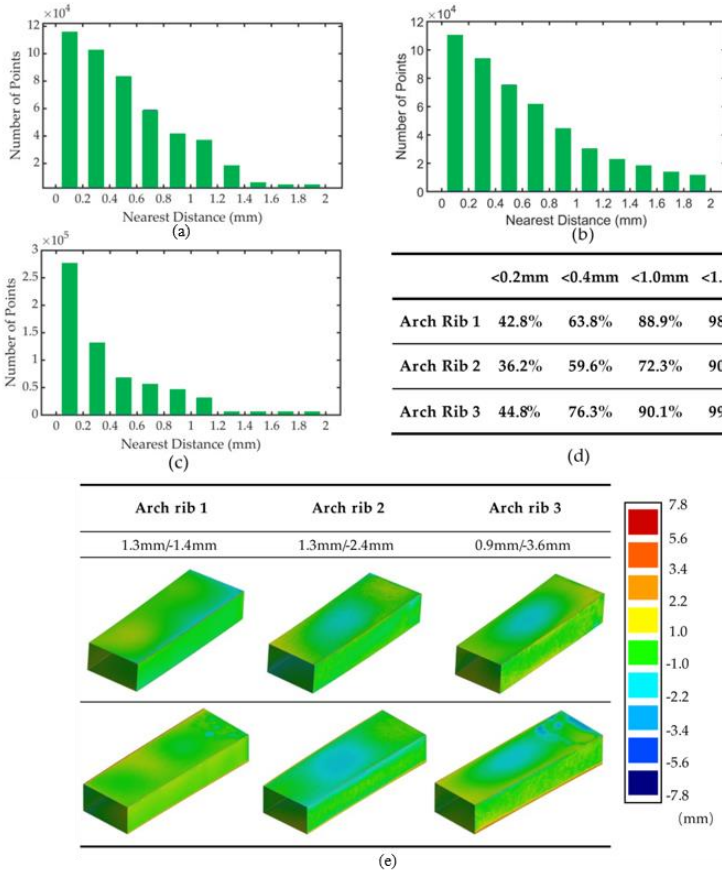


Figure 10: Weld and cut prediction in model

3.2.1 Accuracy analysis

Through comparing the pointwise deviations, the developed approach can provide an accurate modelling of steel box girders (Figure 11), where more than 90% of the deviations of three steel box girders are within 1.6 mm, and 76.3% of deviations of girder #3 are within 0.4 mm.

The deviation analysis of corner points in the VTA model is also conducted on the x, y, and z-axis, including the corner points connecting #1 and #2 girders, and those connecting #2 and #3 girders. These x-axis deviations are the smallest ones, with maximum value of 0.2 mm, as shown in Figure 12. However, the deviations on the Y and Z axes are relatively large, especially for the left and right nodes of the bottom plane, which are around 1mm.



	<0.2mm	<0.4mm	<1.0mm	<1.6mm
Arch Rib 1	42.8%	63.8%	88.9%	98.4%
Arch Rib 2	36.2%	59.6%	72.3%	90.6%
Arch Rib 3	44.8%	76.3%	90.1%	99.1%

Figure 11: (a) Deviations for steel box girder #1 (b) Deviations for steel box girder #2 (c) Deviations for steel box girder #3 (d) Summary of deviations (e) Deviations between point clouds and reconstructed models

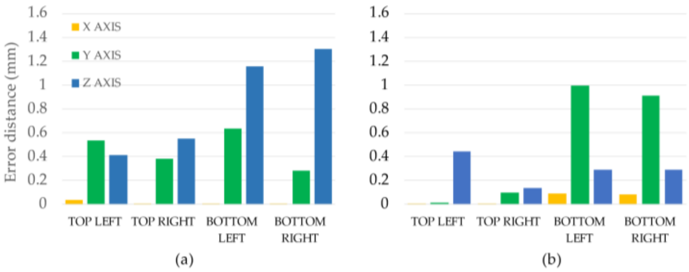


Figure 12 (a) Deviation of corner points connecting girders #1 and #2, (b) Deviation of corner points connecting girders # 2 and #3

3.2.2 Efficiency analysis

The proposed hybrid modelling method in this paper can improve the efficiency of quality inspection and trial assembly of steel box girders. Traditional methods, such as total station and tape measurement, require a large amount of manual measurement and recording, resulting in high time and labour costs, and are susceptible to human factors. In contrast, the algorithm proposed in this paper is based on feature extraction and shape prediction from point cloud data, and possesses advantages such as fast, accurate, and automated. It can rapidly extract the feature information of the steel box girder, optimize the trial assembly linearity through predicted virtual trial assembly, and improve the efficiency and accuracy of trial assembly. This method can also quickly evaluate the quality of the steel box girder and promptly identify and resolve issues to improve the quality and safety of the structure.

4. Conclusions

The proposed hybrid modelling method offers significant improvements in both efficiency and accuracy in the quality inspection and trial assembly of steel box girders. In terms of efficiency, the method's fast, accurate, and automated features lead to reduced costs, improved work efficiency, and increased potential for broader applications. In terms of accuracy, statistical analysis reveals a high level of precision, with more than 90% of the girders exhibiting a maximum deviation of 1.6mm. These findings demonstrate the potential for the proposed method to significantly improve the quality and safety of steel box girder structures. However, it is important to note that this study has some limitations that require further exploration in future work. Firstly, the proposed quality assessment technique was only validated on laboratory samples, which may result in differences between the obtained results and actual engineering outcomes due to the small size of the laboratory sample. Secondly, this study only pre-assembled the three-segment steel box girder, and future research should focus on verifying the trial assembly of the full-bridge steel box girder, which may present greater challenges due to the complexity of boundary conditions.

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