TLS measurements of initial imperfections of steel frames for structural analysis within BIM-enabled platforms

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ABSTRACT

Terrestrial Laser Scanners (TLS) provide manifold possibilities in construction sites. In buildings assembled with steel frames, the “as-built” configuration of the structure can be virtualized by means of TLS measurements in the form of digital 3D point cloud data. This paper presents an integration of procedures related to the reproduction of realistic wire representations of steel frames. This integration encompasses the use of terrestrial laser scanning (TLS) measurements and the development of BIM-friendly wire models based on these measurements. These models are intended to be used in subsequent geometrically nonlinear analysis of the frames using similar BIM environments. All measurements are taken on laboratory tests of sway and non-sway stainless steel subjected to vertical and lateral loading. The “as-built” geometrical initial conditions can be used for the development of models embedded within BIM platforms for their subsequent usage in structural verification.

1. Introduction

The advances in sensing, information and computing technologies continuously provide to the Architecture, Engineering and Construction sector (AEC) ways for dealing with the large variety of technical information at all project stages. The whole project life cycle, from conception, design, construction, to operation and maintenance is nowadays infused with a rising amount of data. The industry faces crucial challenges related to the optimization of these resources since data management may profoundly improve decision-making processes. Conversely, data mismanagement may generate conflicts and data overflow that needs to be avoided. Thus, the integration of data in the form of hubs becomes a paramount task in the years to come.

The manifold forms of visualization, information modelling and simulation (VIMS) are called to be part of centralized information hubs in which all stakeholders establish data flow seamlessly [1]. For more than a decade, information hubs are tending towards semantically rich facility models. Building Information Modelling has gained attention in the AEC sector due to the ability to enhance communication between all players in the different stages of the project life cycle. All information generated at design/construction stages can be put together and updated continuously as the construction project evolves. BIM is particularly attractive in the documentation of “As-built” or “As-is” assets [2].

The generation of an as-built BIM involves measuring the geometry and appearance of an existing facility. Subsequently, those measurements need to be infused within high-level, semantically rich representations with ontologies upon industry agrees. Years ago, detailed measurement of an entire facility required a considerable amount of time and labor force with the up-to-date equipment. Nowadays, both terrestrial laser scanning (TLS) and computer vision–based techniques are increasingly employed in construction sites [3] [4]. The growing computational performance coupled with faster, more accurate and more affordable equipment, allow rendering real-sized objects or assets in the form of dense point cloud data. The creation of the 3D model is increasingly carried out by considering the semantic requirements of BIM environments. The model should not only be a virtual representation of the construction (visualization) but also, a model where the different elements of the building or asset become advanced semantically rich objects (information modelling). Some elements of the model can be seamlessly extracted without redrawing for their use in structural analysis (simulation).

As a matter of fact, structural design plays a major role in building construction. The particular case of structural analysis of spatial or planar steel frames is based upon the classification of the structure concerning its overall stability. Broadly speaking, both European EN1993-1-1 [5] and American AISC [6] specifications, classify as sway frames those frames where the effect of the initial deformation of the structure plays and important role during the structural analysis,
increasing members forces due to the so called 2nd order effects. This effect is especially important in slender structures prone to overall and local buckling [7].

For these sway frames, the second-order effects are considered taking into account the influence of deformations of the structure and performing a geometrical nonlinear global analysis to calculate member forces that need to be compared to the corresponding resistances. The resultant member forces largely depend on the shape and magnitude of the initial deformation, defined in EN1993-1-1 [5] as geometrical imperfection.

These imperfections are, however, unknown a priori and are hence assumed throughout the design stage. Notwithstanding, the as-built initial imperfection of steel frames is seldom documented and/or used a posteriori in simulation and verification of constructed assets. As a consequence, adequate reproductions of planar/spatial frames require careful consideration of all relevant potential failure modes and these representations require the use of proper initial geometric deformations.

Presently, state-of-the-art terrestrial laser scans provide considerably detailed information about spatial geometries. These devices are increasingly used in construction sites for manifold uses ranging from documentation of as-built geometry of the structural system. For instance, the identification of geometries for its integration in BIM environments has been present in academic research [8,9]. The identification of initial deformations (or initial imperfections) from a semi-automated treatment of TLS measurements and its integration on BIM-friendly structural analysis is, however, less developed.

This paper presents an integration of procedures related to laboratory testing of stainless steel frames, TLS-based data-gathering and the automated transformation of the corresponding point clouds to as-built realistic BIM representations of the steel structures. TLS measurements are performed on a set of stainless steel frames subjected to incremental loading up to failure. Point-cloud data is gathered during several test stages, including the unloaded case. Subsequently, a set of mathematical processing of the results is performed for the sake of generating wireframe models. The automatic generation of these structures is developed within algorithmic modelling environments, namely, Grasshopper. The imperfection patterns are identified, processed and analyzed using comparison benchmarks.

The paper is organized by separate sections that encompass: a literature review in TLS-to-BIM and geometric imperfections in structures (section 2), a brief description of laboratory tests set-up (section 3) and TLS measurements (section 4). Interoperability and data workflow in the context of this research are addressed in sections 5 and 6 and finally, results and a discussion related to the potential use of “as-built” data gathered in construction sites are pointed out in sections 7 and 8.

2. Literature review

2.1. Automated point cloud registration in AEC

Research related to automated point cloud registration using TLS is vast. In many fields, laser scanning techniques have been used to collect information related to three-dimensional point clouds of various scenes (e.g., geomorphological, forestry or urban). Laser scanning has developed considerably since it allows collecting dense 3D point clouds of object surfaces quickly and accurately [10]. In geosciences, for instance, long-range laser scanners are routinely employed for the determination of landslides, rock falls and debris displacements [11]. In agriculture and forest engineering, laser scanners allow gathering information related to vegetation evolution and morphology [12,13]. Most published works in the relevant area recognize density and accuracy as the main quality parameters of a point cloud. Several issues such as image occlusion [14], data-processing capacity [15] or data-filtering [16] are specific subjects of research in the field.

TLS applications in the AEC field range from a variety of topics such as analysis of historical constructions [17] to real-time quality control of construction sites [18]. Likewise, at a greater scale, entire urban areas are monitored using TLS for manifold applications such as underground construction technologies [19] or façade identification [20]. The case of single (yet wide) construction sites is particularly interesting. Due to the increasing presence of TLS in construction sites, data-collection of the as-built condition has become one of the most targeted applications in AEC. With the advent of BIM, 3D point cloud data are not only useful for creating CAD-based models but also, for being embedded following standard ontologies in semantically rich models. Reviews articles that focus on the automatic reconstruction of as-built BIM models from TLS point clouds are available [2] [21]. BIM has the potential to advance and transform facilities in a platform for managers to retrieve, analyze, and process building information in a digitalized 3D environment [22]. The model interoperability becomes paramount for the sake of optimizing data-flows and resources [23] [24].

Currently, recognition and modelling of primary components such as the structure, floors, ceilings and walls requires careful consideration of surface modelling as the construction evolves [25]. Techniques referred to Scan-to-BIM and Scan-vs-BIM have been defined separately in the literature as alternative media to document construction sites as they evolve [26]. Extension of automatic Scan-to-BIM beyond these large primary components to other smaller secondary elements [27] or to as-damaged elements have also been addressed [28].

From the perspective of creation of as-built models for their use in numerical simulations, several research works can be pointed out. Methodologies regarding the optimization of FE-models based on TLS measurements were presented in [29]. These authors focused on the development of B-Spline fitting procedures for the development and analysis of models of arch structures. In [30], researchers developed structural simulations using FE-models from geometries of detailed historical constructions with complex architecture. Whole volumes were acquired in the form of point cloud data ans used subsequently. In [31], integration of TLS, deviation analysis and FE-models for the development of FE-based structural analysis of a historic minaret located in Turkey was performed. Stability analysis of masonry leaning structures by gathering TLS data and developing 3D FE-based models have been published [32]. In other structural applications [33] [34], point data treatment represents a major task for the sake of transforming a large amount of data into tractable and accurate simplified models. In the particular case of steel frames, researchers [8] have presented methodologies for the automatic identification and generation of 3D steel structures for BIM platforms by using TLS measurements. The specific focus was on the identification of cross-sections and members. A set of case studies and applications of laser scanning to structures in laboratories and field structures are provided in [35].

2.2. Imperfections in steel structures analysis

Where imperfections should be included in the finite element numerical model for the analysis, they should account for the effects of geometric deviations from the perfect shape of the structure, residual stresses due to manufacturing such as welding, hot-rolling or cold-forming and boundary condition defects (e.g. differential settlement, uneven foundation, etc.).

The initial geometric imperfections caused by manufacturing and erection in steel construction engineering is random and unpredictable. They may be defined as measured imperfection shapes of the structural element, imperfection shapes based on linear buckling analysis (LBA) corresponding to the eigenshape associated with the expected failure mode or modifications of the perfect shape as the member out-of-straightness (bow imperfection, commonly referred to as δ) and local imperfections of thin-walled members (plate imperfection, commonly referred to as ω). Fig. 1 illustrates the relevant geometric imperfections in steel frame for geometric nonlinear global analysis.
For an adequate structural verification, all possible initial geometric imperfections should somehow be taken into account when analyzing steel frames [36] [7]. The pattern of initial imperfections is usually chosen to be the worst-case scenario that triggers destabilizing effects for a set of applied loads. Assuming certain geometric imperfections influences the structural behavior of a frame, especially in those cases in which these systems are prone to global instability increasing internal forces and/or modifying the structural behavior due to second order effects. Guidelines and provisions define several approaches to consider the effects of geometric imperfections in structural analysis of steel frames: i) The use of an adequately scaled elastic buckling mode, ii) the use of nominal horizontal forces, iii) the reduction of member stiffness or iv) the direct modelling of the actual initial geometric imperfections when measured.

The effects of imperfections have been profusely studied at member levels (both δ and ω) [37] [38] [39] and at system levels (Δ and ω for some cases) [40] [41] [42,43]. Likewise, the effect of imperfections has been studied for different structural configuration such as non-prismatic members [44], cold-formed steel members [45], or different connection arrangements [46] [47]. In particular cases, the verifications provided by guidelines are based upon assumptions such as isolated verification of members. In complex 3D structures in which stability interaction effects are observed [48], FE-analyses and the subsequent structural verification require definitions by designers concerning this particular topic. The stochastic nature of imperfections has been also studied by considering these parameters as random variables under probabilistic approaches [7] [49] [50] [51]. Furthermore, laboratory experiments for steel frames and elements in which global and local imperfections are measured have also been reported in the literature [52] [53]. As a result, it is interesting to point out that accurate “as-built” definitions of steel structures provide valuable information for verification of structures and knowing safety margins.

Furthermore, the influence of initial imperfections and residual stresses dealt with simultaneously has also been a topic of study in stability analysis [54-57]. In numerical simulations, residual stresses may be included within the cross-sectional properties in the form of an initial stress field at integration points (for beams) or in the form of a planar stress (for shells). These types of simulations have been primarily used in research in advanced analysis (Geometrically and Materially Nonlinear Analysis with Imperfections, GMNIA). More simplified geometrically nonlinear elastic analysis (GNA) include amplified geometric imperfections only that seeks to encompass both geometric and material imperfection effects.

3. Experimental program

An experimental program on sway and non-sway austenitic stainless steel frames was conducted at the LATEM laboratory of the Department of Civil and Environmental Engineering in Universitat Politècnica de Catalunya. The program comprised tests on both stocky and slender Rectangular Hollow Sections (RHS). The ultimate goal of the research is to assess the currently existing design rules, in terms of predicting ultimate capacities and second order effects in stainless steel frames.

Tests on frames were performed on one-bay, one-storey austenitic stainless steel frames with Rectangular Hollow Section (RHS). The connection between the beam and columns was welded with an auxiliary plate with an inclination of 45°. Likewise, for the connection at supports, additional steel plates provided with holes allowed generating either fixed or pinned boundary conditions. Fig. 2 provides a general overview of the test setup and Table 1 provides geometrical values and conditions for all frames. Two hydraulic jacks applied vertical loads on the beam and a horizontal hydraulic jack applied a controlled incremental displacement at the base. The frame was fixed at one of its corners on the top. Extended reports on the whole experimental program are presented in [58,59]. Other studies on stainless steel frames using numerical methods have been developed at the research group [60,61].

In all frames, the instrumentation was implemented in a twofold fashion. Traditional instrumentation for acquiring data related to the structural response of the frames and an additional set of devices for acquiring data aimed at providing real-time visualization, information modeling and simulation (VIMS) of the tests. Traditional instrumentation was in place and data flowed from load cells, strain gauges, LVDTs, lasers, a theodolite (total station, TST) and hydraulic jacks to Data Acquisition Systems. Details of this instrumentation can be found [58]. The VIMS layer included TLS measurements, computer-vision measurements (a planar Digital Image Correlation system) and displacement sensors for establishing real-time connection with IoT applications developed at the School Civil Engineering of Barcelona facilities as well as with Augmented Reality applications designed for visualization and simulation purposes [62] (see Table 2).

4. TLS measurements

One fixed TLS Leica ScanStation2 was used throughout the whole program. The TLS was located slightly away from the structure with the aim of gathering in- and out-of-plane data of the frame. Since this position was fixed, point cloud data related to only two visible sides of the tubes was gathered. All visible sides of the columns and beams were scanned. Fig. 4 displays the frame and the TLS with a schematic representation of the measurement principle. Together with the TLS, a theodolite (total station) was also used during the tests for the sake of adding verification and control on specific points located on the inner edge of the visible side of the tubes. Initially, the coordinate system origin was located in the position of the TLS. This CS origin was moved to the coordinate system of the study, whose origin was set on the base of the right column as indicated in Fig. 3 as well.

In addition, 4 mm-thick magnetic targets were placed on the frame as well as on determined fixed points of the laboratory facilities (Fig. 4). The targets on the frame allowed tracking the frame movement during the test and the external targets allowed detecting absolute displacements of the whole testing system. The magnetic target results are being studied elsewhere as part of the research project.

Prior to testing, a scan of the visible sides of the frames was performed. This stage corresponded to the initial shape of the frame. Subsequently during the test (whose running time was two hours on average), the frame was scanned at several stages. The TLS recorded...
coordinates $x, y, z$ as well as a light intensity $\alpha$ value for the whole frames before the test started (initial shape), after vertical loading and after failure. After vertical loading, the test was put on hold during scanning (up to 10 min) in order to acquire data for the whole geometry. Scans during intermediate levels of loading were also performed but in this case, the tests were not fully stopped during scanning. Measurements were particularly focused on the magnetic targets at those levels.

### 5. Interoperability and structural analysis

Presently, all design methods based upon Geometrically Nonlinear Analysis (GNIA)- or Geometrically and Materially Nonlinear Analysis (GMNIA) require the definition of an initial deformed shape with structural imperfections or alternatively, the definition of a set of equivalent loads that generate an equivalent deformed shape that include both effects. Since GNIA- and GMNIA- analyses require an increasing level of sophistication in the new generation of Eurocodes, the definition of such initial conditions become a cornerstone of design methods.

When it comes to the unloaded stage of the tests, the TLS-based initial imperfection represented the outcome. This laboratory unloaded stage is also found in situ during the construction process. TLS-based measurements at this stage are comparable to those obtained in the lab and represent the as-built imperfect shape of practical importance for designers.

Experimentally, the primary goal was to obtain TLS measurements and embed processed data on specialized Software for the design of steel structures with a high level of automation. Versatile exchange formats and data treatment are required for such endeavor. First, non-automatic information cleanse was performed using CloudCompare [63]. Subsequently, automatic procedures were implemented in parametric design platforms such as Rhinoceros [64] and Grasshopper [65]. These tools are BIM-enabled and their output can be made compatible with interoperable data files such as IFC [66]. Thus, any geometrical model can be enriched semantically with attributes that are compatible with other BIM-related tools. In the context of this research, Python scripting was used since scripting is facilitated with the Rhino.Geometry namespace. As a result, the implementation of point cloud treatment strategies within algorithmic programming geometrical models becomes an interesting integrative approach in the design of structures in which geometry, structural analysis, optimization and BIM are fused together.

Other BIM-Enabled platforms such as Tekla [67], or commercial Software such as Consteel [68], Pangolin [69], Karamba3D [70] or Sofistik [71], presently use the same environment and can be subsequently used for structural analysis. It is worth pinpointing that similar procedures could be implemented in comparable BIM environments such as Dynamo-Revit [72,73].

### 6. Data workflow

The aim of the scans performed during the tests was to establish a semi-automatic flow of information between TLS measurements (whose
raw data is in a point cloud \(x,y,z,\alpha\) format) and BIM-friendly algorithmic programming hubs. Ideally, full scans of frames taken from different location would provide a full 3D survey of the structures. In this particular laboratory experience, however, TLS measurements were taken from a single location due to safety during the tests. This means that the scanner was able to provide information from two facets of each RHS section (for a total of 6 facets). In order to develop FE-models using beam elements, accurate reproductions of the center line of the elements was needed. Thus, it was necessary to develop a set of algorithmic rules able to transform raw data from six visible facets to a representative single deformed polyline centered in the middle of the columns and beams. It should be pointed out that these platforms would also provide tools and scripting capabilities for reproducing geometries to be used for Finite Element Modelling with shell elements in which other types of instabilities (local or distortional) may be key in design.

6.1. Preparation

The processing of the 3D point cloud consisted of several steps starting by the preparation and cleanse of all points clouds from noise as well as from elements that do not belong to the frame (cables, sensors, magnetic targets and auxiliary supports). The procedure for developing semi-automatic data flow begins with the preparation of the facets. Fig. 5 shows an unfiltered points cloud of one of the tests including auxiliary elements.

An affine transformation consisting of a rotation and translation of the point cloud to place the origin of the Cartesian coordinate system at the bottom right of the frame was performed. With this, the \(x\) and \(z\)-axis contain the outer face of the frame and thus, it is possible to track deformations with a straightforward reference. The point cloud encloses a total of six facets that were separated to subsequent processing.

6.2. From .txt to 3D points

For each frame, the result was a set of points on six facets gathered in six separated .txt files (one per facet). Data was imported by means of a Python script from \((x,y,z,\alpha)\) text form to points instances that are fully operational and retrievable in the virtual space. Fig. 6 illustrates the data acquisition from .txt files (input) to the (output) with the corresponding visualization of results.
6.3. Intersection of facets

Two intersecting facets of a given members (e.g. a column or a beam) define one approximate representation of one of the edges of the RHS section. Interpolated planes were created from a list of points. For a given list, the best fitting plane to the set of points was found. The result is a plane whose components (a 3D point and a normal vector) are retrievable. Two perpendicular facets are characterized by two best fit planes. These planes can also be intersected in the form of an intersection line. By definition, this line has no boundaries.

Nonetheless, one should not use the whole list of points of each facet in such operation. A discretization of the columns and beam elements is needed since if the whole list of points of a facet of a member is used in such interpolation, the result would be a perfectly straight edge along the whole member with no imperfection.

In order to reproduce the initial imperfection of the member, the operator “segment” is defined within the algorithm. This operator slices the list of points in smaller portions. The result is a set of partial point clouds. Best fit planes are also found within those smaller portions and intersection lines are obtained. These entities are lines whose components (a point and a parallel vector) are retrievable within the python script. These lines have no boundaries and are expected to be unparallel from one segment another. Fig. 7 displays a visualization of the whole frame and a highlight of one segment at the beam (two facets). The intersection of such segmented lists of points is a line object that characterizes the highlighted area.

6.4. Intersection of lines

The next step corresponds to finding a set of finite edges from these infinite lines. These edges are put together and should represent an approximation of the realistic imperfect polyline. Fig. 8 displays an idealization of the procedure for finding this polyline on a member with a bow imperfection $\delta$. For the first segment, two best fit planes are intersected and generate an infinite line 1. For the second segment, two best fit planes are intersected and generate an infinite line 2. Subsequent intersections are performed as many times as the defined number $n$ of segments.

When infinite line 1 is intersected with a reference plane that passes across the beginning of the member, point 1 is found. Point 2 results from the intersection of lines 1 and 2 and subsequent points are obtained when intersecting subsequent adjacent lines. The last point corresponds...
to the intersection of line \( n + 1 \) with a reference plane. As a result, a list of 3D points [Point3D\(_1\), Point3D\(_2\), Point3D\(_3\), ..., Point3D\(_{14n+1}\)] define the geometry of the imperfect member. Translating such geometry from the edge of the RHS to its center of gravity represents the final step.

### 6.5. Implementation in BIM-enabled platforms

Fig. 9 displays the resulting algorithmic programming sequence in BIM-enabled platforms, in this particular case, Grasshopper. Algorithmically speaking, Fig. 9 is read as follows:

- Firstly, input .txt files are treated and transformed into geometrical objects. Points, lines and discretized segments are defined using Python scripting.
- Secondly, the resulting objects (planes and lines) are used for intersection purposes. Plane-to-line as well as line-to-line intersecting methods are used in order to obtain the set of points.
- Thirdly, all points are connected sequentially basic definitions of lines between 2 adjacent points. Thus partial edges of the RHS are found.
- Finally, connecting these partial edges results in a final edge that must be translated to the member axis and thus, it can be then transferred to other structural analysis Software within BIM hubs (output line).

### 7. Results

Both in-plane and out-of-plane initial imperfections were measured using: i) a traditional system measuring the visible inner edge of both columns and beam (Total Station) and ii) the post processed TLS measurements and subsequent algorithmic geometrical transformation of the facets. Frames S3 (semi-compact) and S1 (compact) are used for comparison purposes. Both are assembled with tubes presenting one 120 mm side, which makes them comparable from the perspective of point cloud size within the cross-section.

TLS-based initial shapes were initially processed using two discretization levels. The first level corresponds to a 5 segments discretization per element whereas the second to 10 segments. Moreover, total station measurements generated 5 segments per element, which is comparable to one of the studied cases. Those measurements were defined as a Benchmark for comparison purposes. Fig. 10 shows graphical results visualized in the virtual space in which point clouds are transformed to lines and points that are connectable to any other structural analysis plug-in or platform. The obtained points and lines do not form a perfectly straight planar frame. These measurements show deviations in all coordinates \( x, y, z \) that define sway and bow imperfections. In particular, focus is on:

- Shapes and maximum vertical deviations of the beam.
- Shapes and maximum horizontal deviation of the columns (both in-plane and out-of-plane).

The analysis is performed under the assumption of a perfect 90-degrees connection between beams and columns.

The number of segments to be used in such discretization is a
designer-assumed condition. This assumption was assessed systematically on the basis of comparison with the benchmarks. Three indicators were chosen for comparison purposes, maximum vertical deviation along the beam (bow imperfection, Z-coordinate), maximum horizontal deviation of the right column (sway imperfection, in-plane, X-coordinate) and maximum horizontal deviation of both left and right columns (out-of-plane, Y coordinate).

Table 3 shows the obtained results for all frames. Several observations are pinpointed:

- In the vast majority of cases, maximum deviations obtained by discretizing the mesh using 10 segments resulted in higher values.
- The in-plane deviations (both vertical and horizontal), are in good agreement with the measurements from the total station (Benchmark). One exception is frame S2 in which TS measurements at the right column exceed those measured with TLS.
- The TLS out-of-plane deviations practically coincide with those benchmarked.

On the other hand, the obtained shapes using TLS measurements are studied as well. In this case, the comparison is performed using visual inspection of the resulting shape when plotted together with the benchmark in an amplified fashion. Fig. 11 displays the in-plane initial shape of frame S3 (semi-compact with pinned supports) using a 5-segments discretization. Fig. 12 displays the in-plane initial shape of frame S3 using a 10-segments discretization. In both cases, a reference perfect frame is plotted together with the benchmark. For both discretization levels, the shape is similar. Columns tend to deviate inwards and the beam tends to deviate upwards. Qualitatively, bow and sway imperfections are in good agreement as well. It is observed though that the initial shape of the beam (10 segments) presents a peak on the left side. This peak is not observed on the 5 segments reproduction. The peak distorts the shape quite significantly.

As a matter of fact, the 10 segments reproduction shows abnormal changes on the slope of the tangent lines. This observation is more noticeable in the Y-Z plane. Fig. 13 shows amplified out-of-plane deviation plots for both left and right columns (5-segments). Fig. 14 shows amplified out-of-plane deviation plots for both left and right columns (10-segments). The comparison between the shapes and the benchmark are quite satisfactory. Results practically coincide both qualitatively and quantitatively. However, it is observed that increasing the amount of segments tend to increase discontinuities in the slopes of the tangent lines of the obtained shapes. Discontinuities at such levels may undermine the practical use of those lines for GNI- and GMNI- analyses.

Similar observations are pointed out in S1 frame (compact with fixed supports). Figs. 15 and 16 display in-plane initial shape reproductions. Both qualitatively and quantitatively (in their amplified form) coincide satisfactorily. Discontinuities are also observed in the 10-segments reproduction. When it comes to the out-of-plane initial shapes, the similarities between both measurements are considerably high.

Table 3

<table>
<thead>
<tr>
<th>Frame</th>
<th>Number of segments</th>
<th>Maximum deviations (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Beam (vertical, Z)</td>
<td>Right column (horizontal)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Station TLS In-plane (X) Out-of-plane (Y) Total Station TLS</td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>5</td>
<td>2.2</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>S2</td>
<td>5</td>
<td>0.8</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>S3</td>
<td>5</td>
<td>1.5</td>
<td>1.2</td>
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<tr>
<td></td>
<td>10</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>S4</td>
<td>5</td>
<td>4.0</td>
<td>2.0</td>
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<tr>
<td></td>
<td>10</td>
<td>2.8</td>
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</tbody>
</table>
Fig. 11. In-plane initial amplified shape of S3 with a 5 segments discretization.

Fig. 12. In-plane initial amplified shape of S3 with a 10 segments discretization.

Fig. 13. In-plane initial amplified shape of S3 with a 5 segments discretization.
Fig. 14. In-plane initial amplified shape of S3 with a 5 segments discretization.

Fig. 15. In-plane initial amplified shape of S1 with a 5 segments discretization.

Fig. 16. In-plane initial amplified shape of S1 with a 10 segments discretization.
Another point to be discussed is related to outliers. 10 segments reproduction showed a systemic appearance of outliers among the obtained points. One or two points per column/beam were discarded due to the fact that these points presented coordinates outside the boundaries of the frames, which is physically impossible. Closer inspection of these abnormal findings showed that smaller sequential segments presented very small differences between slopes. This fact resulted in intersection of lines that were almost parallel. Consequently, intersection points were found outside the boundaries of the frame. This singularity was not observed in the 5-segments reproductions (sequential lines did not present such level of parallelism). Noticeably, 5-segments discretization delivered better results from the perspective of continuity but also, from the perspective of automation (no close inspection of outliers was needed). However, in some of the cases, the magnitude of the initial imperfections obtained with such discretization was smaller than the more refined segmentation.

8. Conclusions

In this paper, a study of measurement, processing and modelling of initial deformed shapes of stainless steel frames tested in laboratory is presented. Initial deformations, also called geometric imperfections, were measured using traditional Total Station equipment (for benchmark purposes) and a terrestrial laser scanner (TLS). Data processing was performed using scripting developed in Python and embedded in BIM-friendly, algorithmic programming platforms. The “as-built” geometrical initial conditions of such frames were obtained from point cloud data in the form of lines and points defining the center lines of beams and columns. These lines and points can be directly embedded within BIM-friendly platforms and as a result, a subsequent usage in structural verification using both different types of geometrically nonlinear analysis is straightforward. The experimental program consisted in four stainless steel frames with both slender and compact tubular cross-sections loaded vertically and horizontally up to failure. The tests were designed covering both sway and non-sway cases. The measured imperfect shapes cover bow and sway imperfections.

The developed procedure resulted in satisfactory results when compared to the defined benchmarks. Quantitatively, vertical and horizontal deviations obtained using TLS measurements for beams and columns are in close agreement with those obtained with Total Station. Very close agreement of results was observed when comparing out-of-plane deviations. Qualitatively, lines and points obtained with TLS were compared to the benchmark using amplified plots. Both in-plane and out-of-plane shapes are satisfactorily similar. For instance, the presented frames show imperfect shapes with inwards and upwards deviations measured with the benchmarks and the TLS.

Two different discretization levels were studied. The “segment” operator was set to 5 divisions per element and to 10 divisions per element. Quantitatively, a more refined mesh resulted in higher deviation values. Qualitatively, however, a more refined mesh resulted in a discretization with slope discontinuities and operational drawbacks due to the presence of outliers. The segment operator influences the resulting shape and should be studied when applying the presented procedure.

On the basis of this research, a thorough study on the use of TLS-based initial imperfections on GN- or GMNI- analyses was performed. The presented results represent a benchmarked set of frames that will be used for a systematic use of imperfections on structural analysis verifications (GNIA and GMNIA). On the other hand, the set of tests can be used for comparison of similar experiences to be performed in laboratory facilities or ideally, on the construction site.

Finally, it is pointed out that steel frames can be measured using the increasingly accurate TLS available and point cloud data can be transformed to computationally tractable entities with practical applications on the Architecture, Engineering and Construction sector. Several different applications that are based on the actual shape of the built structures can be developed within BIM platforms. For instance, the definition of safety margins for real loading scenarios, e.g., the measurement of the actual shape of the structure when subjected to dead loads, the evolution of the actual shape during tensioning or the evolution of the actual shape due to creep effects. Since the design phases are based on nonlinear analysis in which initial shapes are assumed for dimensioning members, establishing comparisons and analyses between assumed and real shapes would also allow establishing comparisons for safety levels. Standardized comparison procedures are potential tools for tracking safety levels for given scenarios. New generation of BIM platforms available in the market can embed “as-built” geometries for manifold purposes such as Life-Cycle Assessment, traceability, or advanced structural verification along their lifespan. Since BIM platforms are increasingly used in maintenance, a correctly stored “as-built” reproduction of the asset represent a valuable digital information that may be needed in the years to come when evaluating the performance of the built environment.

Declaration of Competing Interest

The authors certify that they have NO affiliations or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers’ bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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