SAFECLADDING PROJECT: PSEUDODYNAMIC TESTING ON PRECAST STRUCTURES WITH HORIZONTAL CLADDING PANELS

Agnese SCALBI 1, Marco LAMPERTI TORNAGHI 2, Paolo NEGRO 3

ABSTRACT

Current design approaches ignore the influence of cladding panels, assuming that they are non-structural elements not interacting with the frame. Unfortunately, the detailing of panel-to-frame connections may give rise to major safety issues in case of earthquake. The SAFECLADDING Project was aimed at assessing current systems and proposing new solutions to overcome the encountered issues. New design approaches have been developed for improving the connection systems between cladding panels and precast reinforced concrete frames in seismic-prone areas. Existing connections were used as often as possible and new devices were proposed. Several test setups have been adopted within the same experimental campaign, corresponding to the envisaged design alternatives: iso-static, dissipative and integrated. Both vertical and horizontal panels have been considered. The paper describes the results obtained with the horizontal-panels arrangement and the comparison with the bare frame (BF), which is the reference for the current design practice that considers panels as non-structural elements. The test sequences were carried out using increasing levels of actions, either with cyclic push-over tests or pseudo-dynamic tests, the latter both for serviceability and ultimate limit states. The experimental programme for horizontal panels and the bare frame resulted in a total of thirteen tests. The results confirm that the behaviour of horizontal cladding panels (HPs) is far from both the BF and vertical panels (VPs) systems: masses and stiffness are altered by this configuration, changing the overall structure response. Indeed, the HPs do alter the overall dynamic response of the building in a more complex manner compared to VPs.

Keywords: Precast structures; Cladding panels; Dissipative connections; Pseudo Dynamic Tests

1. INTRODUCTION

Design approaches have largely ignored the influence of cladding panels, assuming that these panels are non-structural elements not interacting with the frame. European Technical Standards (CEN, 2005; CEN 2004) still consider the cladding panels as non-structural elements, as such not contributing to the seismic behaviour, in spite of the wide range of research activities which have been carried out during the last decades to throw light onto the effects of cladding panels. The structural scheme most commonly used for industrial and commercial precast buildings assumes fixed-base cantilever columns with precast beams placed on top of them. Simply supported long-span roof slabs are set orthogonally to the beams. Reinforced concrete panels are then arranged in either vertical or horizontal arrangement. In a cladding system with vertical panels, the gravity action is naturally carried by foundations, hence columns are not affected by vertical loads and they play a role only to avoid the out-of-plane overturning of panels, while horizontal seismic loads are transferred to roof-beams. Conversely, in the horizontal configuration the cladding panels are often fixed to the structure by means of two support connections at the bottom, carrying the gravity loads, which are directly transferred to columns, and two tie-back connections at the top of the panels, avoiding the out of the plane movement due to the earthquake. The design practice of neglecting the panels during the formulation of the mathematical model leads to a substantial

1Trainee, European Commission, Joint Research Centre (JRC), agnese.scalbi@ec.europa.eu
2Scientific Officer, European Commission, Joint Research Centre (JRC), marco.lamperti-tornaghi@ec.europa.eu
3Senior Scientific Officer, European Commission, Joint Research Centre (JRC), paolo.negro@ec.europa.eu
inaccuracy in predicting the seismic stiffness, strength and ductility. The observation of the post-earthquake damage (e.g. L’Aquila and Emilia-Romagna earthquakes) and the experience in the seismic assessment of existing facilities, have demonstrated that the façade claddings bring a significant contribution on the seismic response (Scotta et al. 2015; Toniolo & Colombo 2012; Zoubek et al. 2016) and should not be neglected. The hesitancy to consider the contribution of the cladding panels might be due to the complex behaviour of Precast Reinforced-Concrete (PRC) buildings. Indeed, the interpretation of the behaviour of PRC structures is not easy, due to the substantial number of parameters contributing to the structural response: different connection layouts between frame and panels, in-plane and out-of-plane behaviours, friction between panels, façade arrangements (e.g. vertical panels or horizontal panels), presence of openings (Colombo et al. 2016a). Consequently, a critical analysis of this part of the structure represents an important issue to assess the actual behaviour and to evaluate the global building response. The cladding-to-structure connections are typically designed only for low out-of-plane horizontal actions, such as the wind loads, or for seismic actions perpendicular to the panel plane (tie-back), therefore it is not surprising that the main cause of connection failures is due to the inadequate resistance in the in-plane horizontal direction. New technological solutions for connectors with proper design approaches are urgently required, considering also the in-plane actions. The research project SAFECLADDING was thus aimed at improving the connection systems between cladding panels and precast reinforced concrete buildings for a correct conception and dimensioning of the fastening system to guarantee good seismic performance of the structure throughout its service life. New design approaches have been considered for improving the connection systems between cladding panels and precast reinforced concrete frames. The main goal was to investigate both the behaviour and the impact of different arrangements (e.g. vertical panels and horizontal panels) according to three different design approaches: isostatic, integrated and dissipative (Toniolo & Colombo 2012). The main issue is that considering precast concrete panels as simple masses, without stiffness, is far from the real behaviour of frame-cladding systems. Indeed, when the drift exceeds the relative clearance, the panels become part of the seismic resisting system. Based on the results of the experiments conducted on VPs, the use of hinges is the most proper way to connect the panel to frame without affecting the global stiffness to achieve the isostatic configuration. Moreover, the recorded results show that a proper sizing of friction-based devices may lead to maximize the dissipated energy (Negro & Lamperti Tornaghi 2017). On the contrary, the issue of HPs, which are the most widely used in the precast concrete practice and show most deficiencies, still remains to be verified. The study presented herein investigates the influence of horizontal cladding panels on the seismic behaviour of the single-storey precast concrete building, designed for earthquake actions according to the Eurocode 8. The experimental programme, entrusted to the European Laboratory for Structural Assessment (ELSA), foresaw different setup arrangements with nine tests on the cladding-to-column connections. The programme was concluded with four tests on the mock-up without any panels. The paper focuses on the results obtained with the horizontal-panels arrangement and the comparison with the bare frame, which is the reference for the current design practice that considers panels as non-structural elements.

1.1 Previous work on horizontal panels

It is commonly acknowledged that the connection is a system composed of frame, panels and devices, which should be adequately designed and verified (Negro & Toniolo 2012; Dal Lago, Biondini & Toniolo 2017; Dal Lago, Biondini, Toniolo, et al. 2017). Much has been done in recent years concerning the interaction of the cladding panels with respect to the global response, in terms of experimental campaigns and to harmonize the rules and standard procedures, but a lot remained to be done (Negro et al. 2013). Despite significant progresses in research, most of precast structures with frame system, particularly the industrial buildings, showed a weakness in the panel to column connections. Quite often the connections fail before yielding of the columns. This confirms that an improper design procedure could lead to premature connection failure without significant dissipation (Colombo et al. 2016b). The experimental results from (Belleri et al. 2016) highlight that the failure mechanisms are related to the top connections. In particular, if the sliding capacity is not sufficient, or is inhibited, premature connection failure is recorded. (Brunesi et al. 2015) from their experiments, highlight the importance of the displacement incompatibility between structural and non-structural elements and the high dependency of the overall cyclic response and related damage pattern on the behaviour of panel-to-
structure connections. If the behaviour of the whole structure is modified by the increase in stiffness and strength that is provided by the cladding panels, negative effects could also be encountered, because of the triggering of brittle mechanisms. Another important aspect related to the horizontal panels is the reduction of the effective height of the column, which is associated to the distribution of the inertia loads on the panels and then to an increase of shear demands in the column. As (Dal Lago, Biondini & Toniolo 2017) explain, an efficient panel-to-column connection should be able to provide strength against the out-of-plane action and adequate ductility to accommodate in-plane relative displacements without affecting the in-plane behaviour (isostatic configuration). When these requirements are not fully satisfied as in the case that a wrong retrofitting solution is implemented, the significant increase of the base shear forces under seismic action could lead to brittle failures. The intervention to retrofit the panel-to-column connection by means of stiff steel angles after the 2009 L’Aquila earthquake is a good example of this and the 2012 Emilia earthquake even more (Magliulo et al. 2014). A case study reported by (Scotta et al. 2015) investigated the friction action between the horizontal panels to consider the claddings as dissipative shear walls in framed PRC buildings. The main idea of the authors was to exploit the ever-present effect of friction to create an intrinsically dissipative device. To do this, they proposed sliding devices composed of steel plates with PTFE slotted elements between the panel interfaces. They used the configuration proposed by (Toniolo & Colombo 2012), who evaluated a so-called “statically determined support system” in which the friction is not considered and an "integrated support system" in which the friction plays a role. The aim of the study of (Scotta et al. 2015) was to take into account the uncertainty in the amount of friction by carrying out a sensitivity analysis by varying the friction coefficient. Their results show that in correspondence with friction increases, both stiffness and dissipation ensured by cladding panels with sliding devices become more effective. A study performed by (Cornali et al. 2017) on the existing industrial building stock, showed that the cladding panels represent the most vulnerable element. The authors investigated the vulnerabilities in terms of economic losses concluding that claddings significantly impact the estimation of the total repair cost. However, to the best of our knowledge, none of the above pieces of work considers the effect of horizontal cladding panels on the structure response. Indeed, it will be shown in the paper that the HPs do alter the overall dynamic response of the building in a complex manner, changing the mass distribution and increasing the stiffness. Furthermore, compared to VPs, the objective to achieve an ideal uncoupled system (isostatic configuration), might be unfeasible.

The study presented herein considers the horizontal cladding panels with particular regard to their contribution to structural behaviour, how they change the structural response with and without dissipative connections and the influence of the friction between the panels and connections.

1.2 Design strategies for Isostatic and Dissipative configurations

To increase the knowledge about seismic performance of existing PRC structures with cladding panels and to investigate new solutions for possible improvements, the different theoretical approaches to connect frame and panels may be classified according to three different design criteria: isostatic, integrated and dissipative (Toniolo & Colombo 2012). As it is known, the frame deformation-demand is allowed by a relative clearance that uncouples the motion of frame and panels. For this purpose, the best way to connect claddings as a simple mass without any stiffness contribution is to create a Double-Hinged Panel (DHP), isostatic configuration, both for vertical and horizontal panels (Figure 1a-b). This design criterion is typically assumed in the current practice for vertical cladding panels. In the case of HPs, some further explanations are necessary. In general, in cladding system with horizontal panels, both gravity actions and seismic actions are transferred to columns. Since the panel-to-column connections aligned to the main axis of the panel are made with difficulty, thus, it would be better to hang the panel on top. This system bears vertical forces, while in some cases horizontal forces may be restrained using other devices at the bottom of the panel. In the current practice, the vertical load of panels was supported by bottom corbels, while horizontal forces were assured by a tie-back, that was a simple retain (Figure 1c). The connection devices involved in the experimental campaign are Panel-to-Column (PtC) connections, which have been inserted into the mock-up columns. However, for HPs, the uncertain friction effect due to the weight of the superimposed panel may also act (Figure 1d). As also reported by (Toniolo & Colombo 2012) the friction effects in the horizontal arrangements represent a
limit to create an isostatic system that does not interact with the frame. The friction between panels and connections, ensures that they act as integral parts of the resistant system. Therefore, the panels create a kind of seismic wall governed by friction which affects the seismic response of the whole structure (Scotta et al. 2015). Indeed, the friction effects between the panel and the bottom corbel are another important aspect which cannot be neglected in the assessment and study of horizontal panels. The latter system, called integrated (Figure 1f), uses four connections placed at the corners of the panel. This configuration is based on the hyperstatic connection with fixed supports that make the panels part of the overall resisting system.

![Figure 1. Design criteria to connect frame to panels.](image)

The dissipative configuration is the combination of the isostatic one with dissipative devices (Figure 1e). In this case, it is worth taking into account that the relative displacement among panels, will be increased from the base to the top of the structure (Figure 1e). This confirms once again that the kinematics of horizontal panels alter the response of the building in a more complex manner compared to VPs. The dissipative connections have been involved in the experiments. The Friction Based Devices (FBD) (Ferrara et al. 2011) and the Dissipative Angles (DA) (Dal Lago, Biondini & Toniolo 2017) have been tested, two kinds of devices which are described in Figure 2.

![Figure 2. Dissipative Angles (a) and Friction-Based Device (b).](image)
2. EXPERIMENTAL CAMPAIGN

Table 1 summarizes the taxonomy of the experimental programme. The experiments, the mock-up and the test sequence were designed to assess the most common cladding systems using the same frame structure. The mock-up was a single-storey building made of six square columns, inserted into pocket foundations. The columns bore four roof beams and seven slabs, with masses comparable to the common construction with this typology. The HPs were tested after the vertical ones, with isostatic and dissipative design criteria, both using a DHP test setup. As for the dissipative design criteria, the tests were conducted with FBDs (1 and 2 FBDs) and DAs. Finally, a sequence of tests took place on the Bare Frame (BF) up to a final “funeral” test.

Table 1. Taxonomy of the experimental programme.

<table>
<thead>
<tr>
<th>Arrangement</th>
<th>Horizontal Panels</th>
<th>Bare Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Criterion</td>
<td>Dissipative</td>
<td>Isost.</td>
</tr>
<tr>
<td>Design Strategy</td>
<td>Double Hinged Panel</td>
<td></td>
</tr>
<tr>
<td>Panel to Panel Connections</td>
<td>2DA</td>
<td>1FBD</td>
</tr>
<tr>
<td>Test Identification</td>
<td>H3b</td>
<td>H1c</td>
</tr>
<tr>
<td>External ID</td>
<td>H0b-1</td>
<td>H0b-2</td>
</tr>
<tr>
<td>Internal ID</td>
<td>g09</td>
<td>g10</td>
</tr>
<tr>
<td>Type of test</td>
<td>CPO</td>
<td>PsD</td>
</tr>
</tbody>
</table>

Each setup was tested using increasing levels of actions, either with Cyclic Push-Over tests (CPO) or with Pseudo-Dynamic tests (PsD). The latter both at Serviceability Limit State (SLS) and at Ultimate Limit State (ULS).

![Figure 3. Layout of Horizontal Panel Arrangement.](image)

A sequence of cyclic deformations was applied, controlling the top displacement of the structure. The cyclic displacement protocol was composed of seven increasing steps made, in turn, of three cycles. In the PsD tests, the roof displacement was in the E-W direction for the mock-up, Figure 3. The displacements were applied to the building roof using two pairs of hydraulic jacks, each one equipped with a load cell. The reference input motion used in the PsD tests was a unidirectional 12 s-long-time history with a PGA of 1.0 g. The local measures of displacements, rotations and deformations were acquired by a scalable network of electrical transducers. More details about each setup are given in (Negro & Lamperti Tornaghi 2017). The sensors to measure the panel kinematics are presented in Figure 4.
3. EXPERIMENTAL RESULTS

The relevance of the horizontal panels is even better explained if compared with the vertical ones, which were already described in (Negro & Lamperti Tornaghi 2017). It was demonstrated that the horizontal cladding panels cause a noticeable increase in seismic stiffness of buildings, leading to a decrease in the fundamental period of vibration and, therefore, to a change in the seismic demand. The connection of HPs to columns may alter the overall dynamic response of the building in a more defined manner compared to vertical panels. In fact, they change both the mass distribution and increase the stiffness, acting like kinematic restraints between columns. The results are presented in terms of maximum displacement ($d_{\text{max}}$), maximum restoring force ($R_{\text{max}}$) and total dissipated energy ($E_d$). The following paragraphs present the results of both Cyclic PO and PsD tests.

3.1 Cyclic Push-Over test results

The cyclic test imposed the same displacement time history to the system, recording the resulting load response. The maximum displacement was limited to 0.9% of drift ratio that corresponds to 63 mm, to avoid any significant damage to the structure, that could jeopardise the subsequent tests.

3.1.1 Comparison between Bare Frame and Double Hinged Panel

The comparison of test results points out interesting issues. Indeed, the results (refer to Table 1 for symbols and taxonomy) indicate a higher load-gap, (Figure 5): $R_{12a-1} = 275kN$, $R_{1a-0} = 155kN$ for the same imposed displacement (63mm). The higher spread reached in terms of restoring force, about 44%, confirmed that the horizontal claddings caused a substantial change in the structural response. The load-displacement graph (Figure 5) shows a wider hysteresis for DHP setup than a BF one, with an increase in stiffness response. The same comparison in terms of dissipated energy shows an important increasing, Table 2. Therefore, the test results confirm the hypothesis of the much more adverse influence of HPs than VPs in the dynamic response of the building. Whilst the two setups are equivalent in the VPs arrangements, in the HPs arrangements the $R_{\text{max}}$ and stiffness are clearly increased. This demonstrates that HPs may change the response of the structure in seismic events, see Figure 5. Furthermore, it also shows that an ideal uncoupled system (isostatic configuration) for horizontal panels is impracticable. Moreover, the friction effects on the total dissipated energy still remains to be quantified.
3.1.2 Comparison of Double Hinged Panels with and without devices

As expected, the comparison between FBDs and DHPs system points out several issues regarding the increase of restoring force and stiffness response of the structure. The L-D graphs of DHPs setup with FBDs show a stiffer central part than the setup without the dissipative devices, Figure 6. The application of one FBD and two FBDs among the panels corresponds to the increase of load, in the amount of +49% and +63% respectively (Table 3). In both cases, moving from the test on DHP without FBDs to tests with single and double FBDs, the linear elastic behaviour becomes hysteretic with wide cycles, especially for the H1b-1 setup. Indeed, the value of the dissipated energy increased dramatically from $E_d^{H2a-1} = 99.4$ kJ to $E_d^{H1b-1} = 597$ kJ, about six times higher (Table 3).

Figure 6. Comparison between cyclic tests results with and without FBDs in DHP setup.
### 3.1.3 Comparison between dissipative devices: Friction Based Devices and Dissipative Angles

The setup with the Dissipative Angles (DA), flexible devices used to restrain horizontal forces, shows a very thin hysteresis loop if compared with single and double FBDs. Figure 7 confirms that the FBDs play a key role in the cyclic response of the whole structural system. Indeed, the hysteretic behaviour of tests H1c-1 and H1b-1 (Figure 7b-d) was primarily characterised by stiffer evolution and then, in both cases, the slope decreased until the peak load was reached. The hysteresis loop of DA setup was different in shape. The results comparison indicates that, in term of both load and energy dissipation, the DA setup was very far from the FBDs system (Table 4). In detail, the DA setup resisted peak load approximately 45% and 59% lower than those shown by FBDs for the same displacement (63mm). The same quantitative comparison reports a larger percentage for energy-gap: -83% from $E_{dH1c-1} = 403\text{kJ}$ to $E_{dH3b-1} = 65.1\text{kJ}$ and -89% from $E_{dH1b-1} = 597\text{kJ}$ to $E_{dH3b-1} = 65.1\text{kJ}$ (Table 4).

![Comparison between test results of DHP with FBDs and DA in cyclic tests.](image)

Table 4. Experimental results: comparison between DHP with FBDs and DA in cyclic tests.

<table>
<thead>
<tr>
<th>Design Criteria</th>
<th>Test Id.</th>
<th>Force [kN]</th>
<th>Energy [kJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHP - no devices</td>
<td>H2a-1</td>
<td>g08</td>
<td>275</td>
</tr>
<tr>
<td>DHP – 1 FBD</td>
<td>H1c-1</td>
<td>g06</td>
<td>549</td>
</tr>
<tr>
<td>DHP – 2 FBD</td>
<td>H1b-1</td>
<td>g03</td>
<td>750</td>
</tr>
<tr>
<td>DHP - no devices</td>
<td>H2a-1</td>
<td>g08</td>
<td>275</td>
</tr>
</tbody>
</table>

A very interesting issue appears by a direct comparison between DA setup and DHP system without FBDs. The two systems are indeed equivalent in terms of $R_{\text{max}}$ and stiffness, and the hysteresis loops are very close to each other (Figure 8). Differently from FBDs, the dissipative angles do not influence the global structural behaviour, still, at the same time, they maintain an appreciable increase in the restoring
force. Thanks to this difference, the DA setup can be used to enhance the overall dissipation capacity without adversely affecting dynamic properties. However, the influence of friction effects might need to be examined in depth.

![Comparison between DA and DHP setup without FBDs in cyclic tests.](image)

Figure 8. Comparison between DA and DHP setup without FBDs in cyclic tests.

The backbone curves in Figure 9 present the results obtained by DHP with DA setup and different numbers of FBDs, both compared with the bare frame system. The slope of the graph represents the stiffness of the system. It is worth mentioning that with the FBDs the stiffness has the highest increase, while the slope changes with the DAs reaching a good agreement with the setup without the FBDs. The bare frame mock-up shows about a half of stiffness of DA setup.

![Backbone curves from the cyclic tests in DHP setup with increasing number of FBDs or DA devices.](image)

Figure 9. Backbone curves from the cyclic tests in DHP setup with increasing number of FBDs or DA devices.

### 3.2 Pseudo-Dynamic test results

In those tests, the equation of motion was formulated in terms of a single degree of freedom, with the roof displacement $x$ parallel to the direction of the excitation at the centre of mass of the roof. The selected seismic action was represented by a real accelerogram (Tolmezzo 1976) modified to fit the Eurocode 8 response spectrum type B for all over the considered frequency interval. The accelerogram was scaled with reference to the PGA of 0.18 g for the SLS, and 0.36 g for the ULS. Figure 10 shows the behaviour of different design criteria subjected to the ULS earthquake intensity, according to the mock-up building design. In each case, the output is compared both to the recorded load and the hysteresis loop. It is worth noting that the setup for DHP without connection has not been considered in the PsD test results and only BF setup is used for the comparison. The simple observation of the overlapping of the hysteresis loop, Figure 11a, confirms that the DA setup (H3b-3 test) progressively...
increased the system displacement with respect to the 1 FBDs (H1c-3 test) and the 2 FBDs (H1b-3 test) with a decrease in restoring force of -8% and of -29%, respectively. Contrarily, if compared with the BF setup (O1a-2), DA setup showed a higher capacity to restrain the horizontal absolute displacement of the structure. As it has been already noted, the friction between the panels could play an important role in the global response of the system. The setup with the DA, in which flexible devices were used to restrain horizontal forces, is a very meaningful issue. The interest of the comparison becomes clearer if made in term of dissipated energy, Figure 11b. By a direct comparison between different setups, it seems that the behaviour of the DA system is very close to the one of the BF but the energy dissipation is comparable with the setup with 2 FBDs. The DA system, indeed, contributes to a greater energy dissipation without changes in the global behaviour of the structure. The predicted behaviour is confirmed by the results presented in Figure 12. The DA setup is compared both to BF and DHP setups with 1FBD and 2FBDs. A strong reduction of displacement ($d_{max}$) was obtained by means of the dissipation devices and, as stated for VPs, a low reduction was recorded between 1 and 2 FBDs.
In terms of restoring force, the increasing of FBDs led to the higher load, and the advantage of DA is once again highlighted by its capacity to limit the maximum load in agreement with the original structural response. Moreover, the difference with BF, which is the reference in which panels are treated as non-structural elements, is lower. A most accurate analysis of the energy dissipation of these dissipative devices is possibly needed and it will be addressed in-depth in future research.

4. CONCLUSIONS

All the results have been compared to each other and to the response of the bare frame, which is the reference for the current design criteria. For the HPs different theoretical approaches have been assessed using different design strategies, which were represented by several test setups within the experimental campaign. Contrary to VPs, the tests have demonstrated that the HPs cause a noticeable increase in the stiffness of buildings if compared with the bare frame, which might lead to a change in the seismic response. Comparative analyses, conducted considering different setups, have confirmed the adverse effect on the structure response. Moreover, results demonstrate that the uncoupled motion of frame and panels using an isostatic configuration for the horizontal arrangement is impracticable. For this reason, more attention is needed in the design and assessment of structures with horizontal cladding panels. As expected, the reliability of FBDs has been confirmed by an increased energy dissipation, though combined with a stiffness increase in the mock-up. On the other hand, the findings from DAs, which corresponded to a good performance, demonstrate that it is possible to increase the seismic performance of the structures without changing the overall behaviour. An open issue to be solved for DAs is to quantify the share of the dissipative contribution of the connections and of the friction effects on the total dissipated energy. Indeed, the experiments show that the HPs are highly sensitive to the friction effects between panels and bottom corbels. This research highlights that many possibilities do exist to maximise the dissipated energy, reducing the maximum displacement while enforcing a load limitation. The importance of this topic is also related to the wider use of the horizontal arrangement with respect to the vertical one in precast concrete buildings. The consequence is that higher hazards, in terms of economic and serviceability losses, are tied to horizontally arranged cladding panels.
5. ACKNOWLEDGMENTS

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6. REFERENCES


