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In-plane seismic response of a fastening system for horizontal concrete cladding panels in RC prefabricated buildings

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Abstract

This paper presents experimental and analytical investigation of the fastening system typically used for horizontal cladding panels in RC precast industrial buildings in Central Europe. The considered system consists of two main parts: a pair of top bolted connections, which provide the horizontal stability of the panel, and a pair of bottom cantilever connections, which support the weight of the panel. Based on experimental tests, the in-plane response mechanism of the fastening system was identified. It consists of three distinct stages: sliding with limited friction, contact with the panel causing an increase in stiffness of the connection, and the failure. In the sliding phase, there are only very small friction forces between elements. Significant relative displacements of a couple of centimetres can occur between the panel and the column. After the contact of the connection element with the panel, there is a significant increase of forces, which is followed by a practically brittle failure of the connections. It has been found that the capacity of the complete system is limited by the displacement capacity of the top connections, which are the weakest components. Non-linear numerical models for dynamic analysis were formulated in the OpenSees framework. The typical Coulomb friction model was used to describe the friction in the top connection, whereas the response of the bottom connection during the sliding phase was better simulated with viscous friction model. The contacts that occur when the gaps in connections are depleted were simulated by an instant increase of the connection's stiffness. The numerical models were validated by the tests in cyclic static and in fully dynamic conditions. The results show a reasonably good match between experimental and numerical response.

Key words: precast buildings, horizontal cladding panels, connections, numerical modelling

1 Introduction

One of the most common structural systems in Europe are reinforced concrete precast structures. Because of their open space, fast construction and relatively low costs, they are widely used for industrial and commercial purposes with tens of thousands visitors per day. As observed during recent earthquakes in Italy, damage or collapse of RC precast buildings could have caused human casualties and considerable economic losses [1-3]. Several failures of cladding panels were observed, for which the most probable reasons were failures of the fastening systems. The design practice was not adequate, since it considered only the forces in the out-of-plane direction, instead of more critical response in the plane of panels [4, 5]. Obviously, the understanding of the response behaviour of cladding connections was insufficient.

To avoid destructive earthquake consequences and improve the knowledge about the seismic response of RC precast buildings, the comprehensive experimental and analytical studies have been performed within several EU research projects [6, 7] and some parallel researches [8-10]. Within most recent EU project SAFECLADDING [11] and national project *Seismic resilience and strengthening of precast industrial buildings with concrete claddings*, funded by the Slovenian Research Agency, different types of cladding connections have been studied. The part of the research performed at the University of Ljubljana was devoted to the connections widely used in existing buildings in Central Europe for attaching vertical and horizontal concrete panels to the main precast structure [12, 13].

In this paper, a part of the research campaign concerning the connections for horizontal panels is presented. The main part of the aforementioned project present the full-scale shake table experiments on the precast structure. To be able to set up these complex tests, several cyclic and dynamic test of top connections and complete fastenings system have been performed with the main aim to identify the inplane seismic response mechanism of single connections and capacity of the complete fastening system. Experimental results were then used to formulate appropriate numerical models in the OpenSees software framework.

2 In-plane response of the fastening system for horizontal cladding panels

2.1 Description of the fastening system

The investigated fastening system is one of the most common systems used in Central Europe for attaching of horizontal concrete panels to the RC precast structure. Such structural system typically consists of an assemblage of cantilever columns, tied together by roof beams and girders. Peripheral cladding panels can be differently vertically oriented. Horizontal panels have the width larger that height and are usually attached to the columns (see Fig.1a), whereas vertical panels have the height larger than the width and are attached to the beams of the main precast structure.

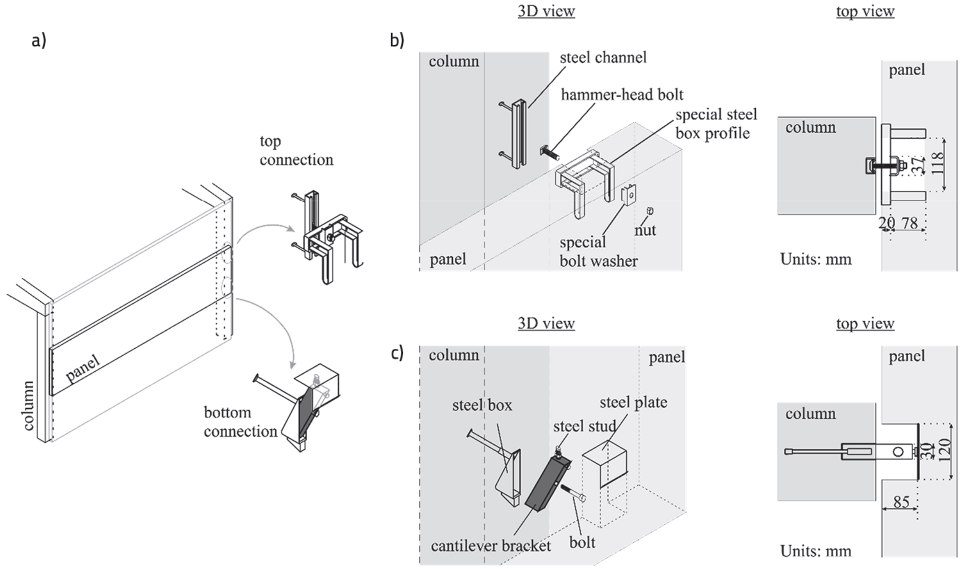


Figure 1. a) Scheme of a typical horizontal panel with cladding connections, b) the assembly of the top bolted connection and c) the assembly of the bottom cantilever connection

The investigated fastening system consists of two main parts: a pair of top connections, which provide the horizontal stability of the panel, and a pair of bottom cantilever connections, which is used to support the weight of the panel. The top connection is the so-called bolted connection and is installed in top corner regions of the panels. As shown in Fig. 1b, the main part of the top connection is the hammerhead bolt. It is inserted in a vertical steel channel built into the column, and connected to a special boxshaped element, which is cast in the panel.

The so-called cantilever connections are installed at the bottom corners of the panel. Each bottom connection consists of a special steel box that is inserted into the column before casting, a cantilever bracket and a steel plate cast into the panel (Fig.1c). During the mounting, the steel bracket is first anchored to the column by a diagonal bolt. After that, the panel is placed on the cantilevers and finally secured at the top with hammer-head bolts.

2.2 The response mechanism of the fastening system

To identify the in-plane response mechanism of the fastening system, two sets of cyclic and dynamic component tests were performed. Only the top bolted connections were tested in the first set, whereas the other set of tests was performed on the complete fastening system, including both top and bottom connections. Altogether, four quasi-static cyclic and six dynamic experiments were performed.

The observed response mechanism consists of three main stages, shown in Fig. 2 and Fig. 3 for the top and bottom connection, respectively. Stage 1 in Fig.2a represents the initial position of the top connection. After the static friction provided by the tightened bolt is reached, the bolt slides along the steel box cast in the panel (Stage 1-2 in Fig. 2). At this phase, a limited friction force is activated. Its amount depends on the tightening torque in the bolt and friction coefficient between steel elements. At Stage 2 (Fig. 2b) the bolt washer reaches the edge of the steel box. At this point, the stiffness of the connection instantly increases. Plastic deformations of the bolt and the channel cast in the column gradually increase (Fig. 2c). The connection typically fails because of the considerable deformations of the channel and pulling-out of the bolt.

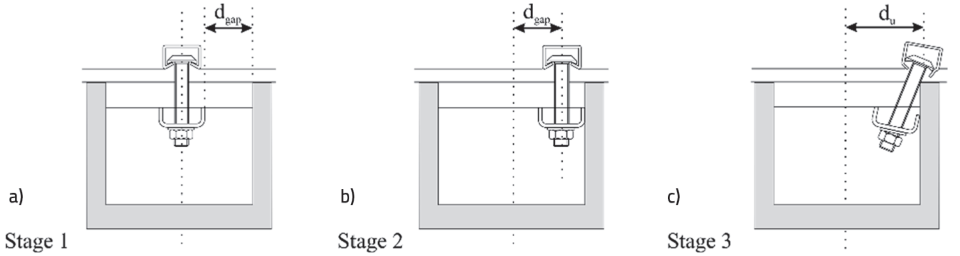


Figure 2. The behaviour mechanism of the top bolted connections: a) initial position, b) the contact of connection parts, and c) the failure of the connection

The response mechanism of the bottom connection is similar (Fig. 3), except that the friction observed in the first phase (between Stages 1 and 2 in Fig. 3) was much smaller than at the top connection. After the gap in connection is depleted (Fig. 3, Stage 2), the stiffness of the connection increases considerably due to the bending of the cantilever bracket. From this point on, the response of the bottom connection is predominantly elastic due to the large stiffness of the cantilever bracket.

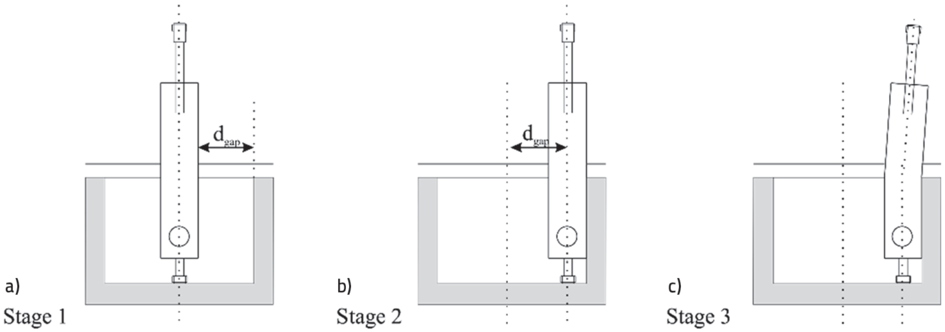


Figure 3. The behaviour mechanism of the bottom bearing cantilever connection: a) initial position, b) contact of the cantilever bracket and the panel, and c) minor deformations at the end of the test

In Fig. 4 typical response envelopes for the pair of top connections and the complete fastening system consisting of a pair of top connections and a pair of bottom connections are shown. Different stages of the response mechanism are marked with dots. When the complete fastening system is considered a significant increase in lateral stiffness can be observed twice (Fig.4b). Stage 2a in Fig.4b indicates a moment when there is contact in the top connections, and Stage 2b in Fig. 4b represents the moment when there is contact in the bottom connections.

Tests of the complete fastening system were terminated before the failure because of the limited actuator's capacity. However, at the end of the test, the bolt and channel at the top were deformed considerably, whereas the bottom connections suffered only minor deformations. It was established that the failure of the system would occur due to the failure of top connections at a displacement of approximately 3.5 cm after the gap in top connections in depleted. Estimated failure of the complete fastening system is presented with a hatched line in Fig. 4b.

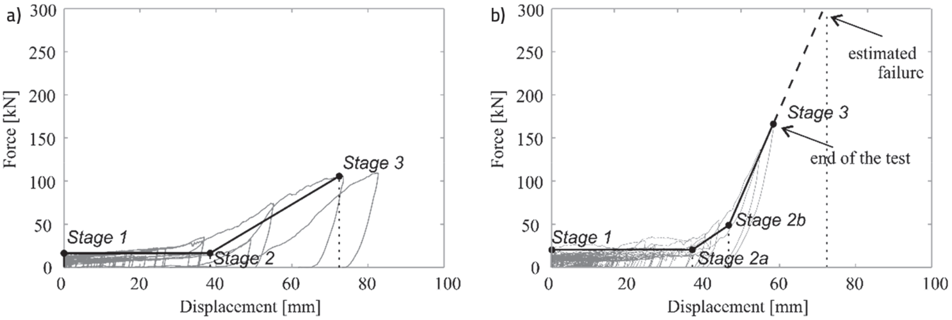


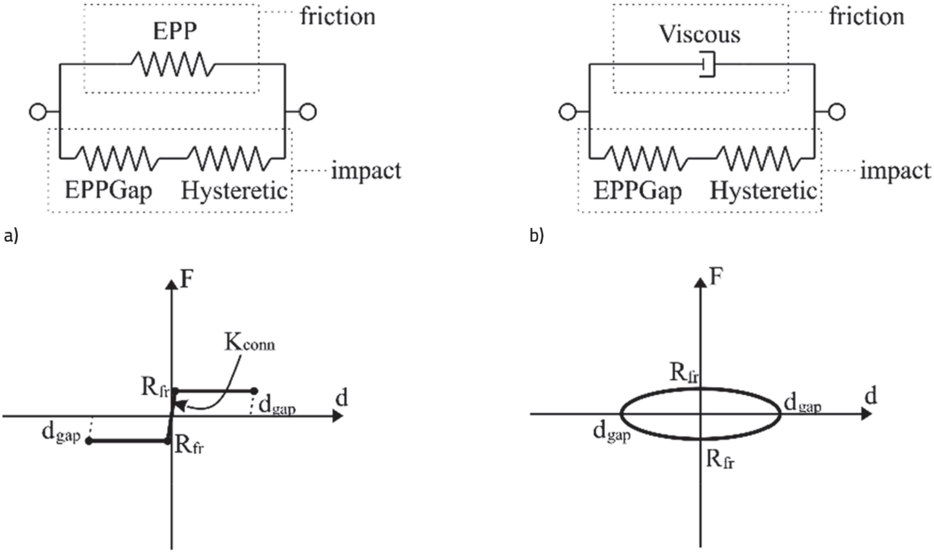
Figure 4. Response envelopes of: a) the top connections and b) the complete fastening system

3 Numerical models

A numerical model for simulating the in-plane response of top and bottom connections was formulated in OpenSees program [14] by combining several standard uniaxial material models. A typical response of the connections was simulated by combining three different material models presented in Figures 5a and 5b. In general, the complete model of the connection was defined with a parallel combination of friction and impact models.

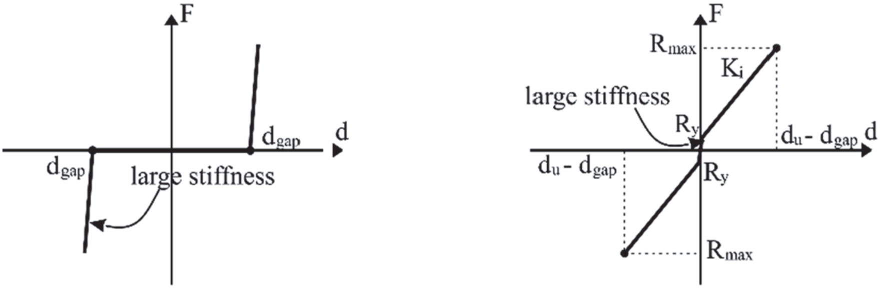
To simulate the friction in top connection during the sliding phase the *ElasticPP* model was used as shown in Fig. 5c and to simulate the variable friction in bottom connection the *Viscous* material model was used (Fig. 5d). For both top and bottom connections, a series combination of the *ElasticPPGap* (Fig. 5e) and *Hysteretic* material models (Fig. 5f) was used to simulate impacts when the gap in connection closes.

The force-displacement and force-velocity responses of the top and bottom connections observed during the dynamic experiments are presented in Fig. 6. The friction response of the bottom connection under the dynamic loading had somewhat different characteristics from the top connection's response. As shown in Fig. 6a and 6b the top connection exhibited typical Coulomb friction behaviour, where the friction force is a product of the normal force on the contact surface and the constant coefficient of friction between the surfaces. The response behaviour of the bottom connection was estimated by subtracting the results of the tests on top connections from the results of the complete fastening system. As shown in Figures 6c and 6d, the friction force in the bottom connection was not constant during the dynamic tests. It was considerably affected by the velocity of connections' excitations and damping, and the viscous friction model was found to be more appropriate. It assumes that the friction force is a linear function of the sliding speed.



c) ElasticPP

d) Viscous



e) ElasticPPGap

f) Hysteretic

Figure 5. The numerical macro model: a) numerical model of the connection, b) numerical model of the bottom connection under dynamic loading, c) *ElasticPP*, d) *Viscous*, e) *ElasticPPGap* and f) *Hysteretic* material

The first analysis of single component tests showed that the response of the bottom connections was rather viscoelastic (as evident in Fig. 6c), which implied that the parallel combination of *Viscous* and *Elastic* models would be appropriate for the simulation of friction in the bottom connection. This model was used for the simulation of single component tests in previously published research [13]. However, it is difficult to explain the physical importance of the elastic spring in the bottom connections, since there is no obvious source of stiffness during the sliding phase. Experimentally defined elastic stiffness was relatively small, and in principle, the viscous friction is usually modelled by taking into account only *Viscous* material model. For this reason, the viscous friction model presented in Fig. 5b is better. It was also verified afterwards with the simulation of shake table tests.

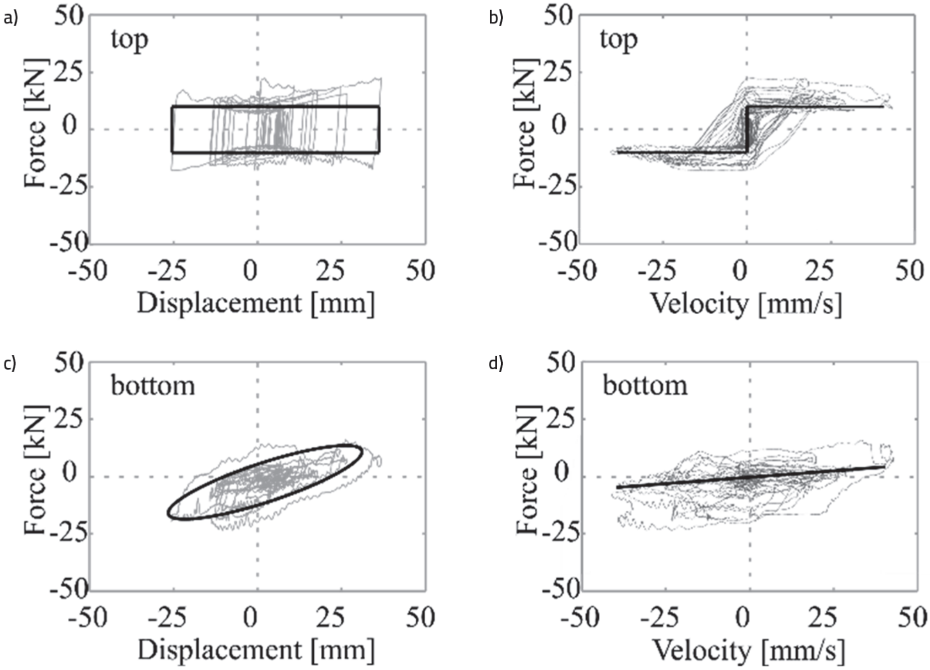


Figure 6. Hysteretic responses (grey) and idealized envelopes (black): a) top connections F-d, b) top connections F-v, c) bottom connections F-d and d) bottom connections F-v

To model the friction in bottom connection during the quasi-static cyclic tests, the common Coulomb model was taken into account since there were no dynamic effects. Thus, this model was similar as used for modelling the top connections response (Fig. 5a).

3.2 Experimental versus numerical response

Recommended values for the model parameters are summarized in Table 1. They were also used for simulation of the experiments and are presented more in detail in the following paragraphs.

Table 1. Recommended values for the model parameters of the connections

Material characteristic	**Value**
Initial gap at the top connection: $d_{gap,top}$ *	±4.0 cm
Initial gap at the bottom connection: $d_{gap,bottom}$ *	±4.5 cm
Displacement capacity: d_u *	±7.5 cm
Friction coefficient of the top connection: $c_{fr,top}$	0.4
Friction force at the bottom connection (cyclic loading): $R_{fr,bottom}$	2 kN
Viscous damping coefficient (dynamic loading): $c_{visc,bottom}$	50 t
Initial stiffness of the top connection: $K_{conn,top}$	$2{\cdot}10^4$ kN/m
Initial stiffness of the bottom connection: $K_{conn,bottom}$	$2{\cdot}10^3$ kN/m
Bending stiffness of the top connection: $K_{i,top}$	$1.5{\cdot}10^3$ kN/m
Bending stiffness of the bottom connection: $K_{i,bottom}$	$1.5{\cdot}10^4$ kN/m
Unloading stiffness after the gap is depleted: K_L	$1{\cdot}10^4$ kN/m
Relatively small yielding parameter: R_y	0.01 kN
px, *py*, *d1*, *d2*, *b*	0, 0, 0, 0, 0
* The value corresponds to the centrally positioned connections	

Size of the gap d_{gap} is the half width of available space in the panel reduced by half of the thickness of bolt washer at top connection or half of the thickness of the cantilever bracket at bottom connection. The connections' initial position depends on the actual construction and the possible residual displacements after the earlier excitation. During the tests, the connections had an ideal position in the middle of the available space. Displacement capacity d_u of the fastening system is defined with the displacement capacity of the top connections. It consists of the variable gap in the top connections $d_{gap,top}$ and the plastic deformation capacity of the bolt about 3.5 cm. If the connections are installed centrally, the total displacement capacity amounts to 7.5 cm.

Friction force in the top connection $R_{fr,top}$ depends on the tightening torque in the bolt and coefficient of friction between the connection parts $c_{fr,top}$, which is 0.4 for this type of connections. During the tests, a maximum friction force of 8 kN was observed in each of the top connections. In real structures, this force might be smaller due to uncontrolled tightening and loosening of the bolt during excitation.

The friction force in bottom connections $R_{fr,bottom}$ was estimated to 2 kN. For modelling of friction in bottom connection during the dynamic tests, the damping coefficient $c_{visc,bottom}$ of 50 t/s was defined. It was estimated based on the velocity and friction force measured in the tests and corresponds to a force of 2 kN at a velocity of 0.04 m/s.

The initial stiffness of connections K_{conn} is very large as long as the friction force and sliding of the connections are not activated. After that, stiffness of the connections is almost zero until the gap closes, and the stiffness instantly increases. Activated bending stiffness of the bolt at the top was estimated experimentally and analytically, and it is recommended to use stiffness $K_{i,top}$ of $1.5{\cdot}10^3$ kN/m in the numerical model.

The impact stiffness of the bottom connection was experimentally estimated from the maximum force and displacement at the failure of the complete fastening system and amounted to $3 \cdot 10^3$ kN/m [13]. However, it was found out during the calibration of dynamic test on a complete fastening system and shake table simulations that the impact stiffness of the bottom connection is much larger. To be able to simulate the response of the connections accurately, impact stiffness of the bottom connection was ten times larger than the impact stiffness of the top connections. Thus, it is recommended to use stiffness $K_{i,bottom}$ of 1.5 10^4 kN/m for the simulation of impacts at the bottom connection.
It was necessary to define specific parameters for the *Hysteretic* material model. To model the response after the gap is closed, the following parameters should be set to zero: *pinchx*, *pinchy*, *damage1*, *damage2* and *beta*. Relatively small parameter R_y and large stiffness K_L were used to define the steep unloading branch.
As shown in Fig.7, the proposed numerical models simulate the response of the connections with a quite high accuracy for top connections tests (a) as well as for cyclic (b) and dynamic (c) tests on the complete fastening system.

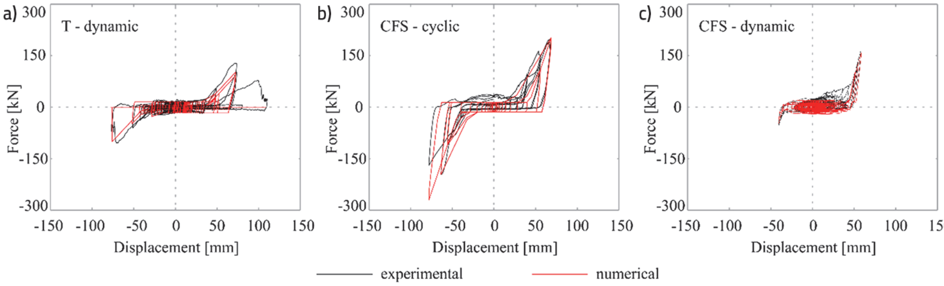


Figure 7. The experimental (black) and numerical (red) hysteretic responses of: a) only the top (T) connections, b) the complete fastening system (CFS) during the cyclic tests and c) the complete fastening system during the dynamic tests

4 Conclusions

The basic response mechanism and numerical model of the fastening system, which is typically used in Central Europe to attach horizontal cladding panels to the columns of RC precast buildings is presented. The fastening system is built of two parts: top connections for providing the horizontal stability of the panel and bottom connections for ensuring vertical support.
It was found that a typical response mechanism of the fastening system consists of three distinct stages: sliding, contact with the panel and failure. The system's displacement capacity is defined with the displacement capacity of the top connections, and it depends on the construction tolerances and the initial size of the gaps.
Relatively simple numerical models were proposed for the top and bottom connections, respectively. They were used to simulate tests and reproduced the response of single top connections and the complete fastening systems with high accuracy.

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